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THERMAL PREPARATION OF FILM FOR USE IN THE OPEN SKIES F.O.C. TREATY VERIFICATION PROGRAM

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13. ABSTRACT (Maximum 200 words)
The Open Skies FOC surveillance aircraft's (WC-135B) thermal environment is constantly changing per mission profile. Supplementary heating and cooling equipment is required on board the aircraft to maintain environmentally controlled temperatures for the preparation and storage of exposed and unexposed film. Temperature chambers located within the Transparency and Thermal Systems Laboratory (TATLAB) were used to demonstrate the thermal performance of electrically powered Norcold TEK-II coolers and a similar-sized heater in meeting the Open Skies FOC cooling, heating, and storage requirements. The coolers and heater, instrumented for temperature measurement and thermostat-regulated operation, were examined over the expected operational range of WC-135B environmental conditions. This report documents the findings of the Transparency and Thermal Systems Laboratory in-house tests and offers installation/design recommendations. In addition, the experimental results have been recorded herein as comprehensive tables useful to Open Skies personnel in predicting film temperatures based upon mission conditions.

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FOREWORD

This report summarizes the complete activities of the work performed by the Flight Dynamics Directorate's Thermal Systems Section (WL/FIVE-2) on the behalf of the portion of the Open Skies F.O.C. Program directed by ASC/AMA. The work entailed the experimentation and analysis of equipment purchased and designed to condition various types of film to mission-appropriate temperatures and to provide adequate thermal storage conditions for the film. The project engineer and author was Mr. Murray E. Johns (WL/FIVE-2). The author gratefully acknowledges the time and assistance of Messrs. Chet Brewster, Dave Brown and Roger Carr (all of WL/FIVE-2).

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1.0 INTRODUCTION

Proper preparation and storage of the various film types used in the exercises of the Open Skies Treaty Verification Program require heating and/or cooling the film to satisfy mission and camera-ready requirements. The equipment proposed to accomplish the film preparation/storage objectives includes off-the-shelf recreational vehicle coolers purchased by ASC/AMA and a film heater designed and manufactured under the oversight of the same organization. The Transparency and Thermal Laboratory (TATLAB) of Wright Laboratory was employed to investigate the thermal performance of the coolers and heater under various combinations of film loads, film temperatures and ambient temperature conditions.

1.1 Equipment

The major tools used by the TATLAB to conduct the experiments included two temperature chambers (33 cubic feet and 8 cubic feet, respectively) with a -100 °F to 350 °F operating temperature range. In addition, a data acquisition program was set up to acquire temperature data from a multitude of thermocouples.

The coolers - a total of four were involved in the experiments - were the Tek II series (model number MRFT-360D) distributed by the Norcold Division of the Stolle Company. The cooler serial numbers were QMN-0041, QMN-0037, QMN-0079 and QMN-0081 (hereafter referred to as Coolers 1, 2, 3 and 4, respectively). In addition, with the exception of a few preliminary tests, all cooler experiments were conducted with the coolers' control dials set at the maximum cooling position. Instrumentation involved with the cooler experiments is discussed below.

The film heater, constructed of various aluminum alloys, was designed to provide conduction heating to as many as 10 large film canisters and 3 VHS cassettes in individual cassette boxes. The part number assigned to the heater is 9340106-1. Heating was provided by four heat pads adhered to the underside of the aluminum film trays.

Details concerning the control of the heat pads and the instrumentation of the film heater are provided below.

Two sizes of photographic film, provided by NAIC, were used in the experiments. The large film canisters (8.5 in. diameter, 5.5 in. height) contained 1000 feet of Kodak Aerocon Film (SO-050, Sp-884) and weighed approximately 11.5 pounds each. The small canisters (6.5 in. diameter, 5.5 in. height) contained 350 feet of Kodak Recording Film (2430 and 2494 Sp-883) and weighed approximately 6 pounds each. Both the large and small film canisters, with the exception of the instrumented canisters, were kept in a sealed condition throughout the experiments. In addition, 3M T30 and one T120 Professional Videocassettes (in plastic cases) were used in the experiments. The single T120 videocassette was chosen for instrumentation. A discussion of the instrumentation of some of the film canisters is presented below.

2.0 METHODS, ASSUMPTIONS AND PROCEDURES

An initial project plan was developed prior to the experimental procedure and hardware configuration. The plan specified the required instrumentation, test equipment and test parameters necessary to conduct the experiments. The details of this plan are elaborated below. However, during the course of the experiments, it became necessary at times to alter the experimental hardware and to change some of the test procedures and parameters, thus deviating from the original project plan. These deviations are explained more clearly in the section of this report outlining the results of the experiments and project.

2.1 Instrumentation

A total of six thermocouples were situated within each of Coolers 1 and 2. Figure 1 shows the internal locations of several of the thermocouples: cooler front wall; cooler center; cooler bottom; and, cooler side. An additional thermocouple not

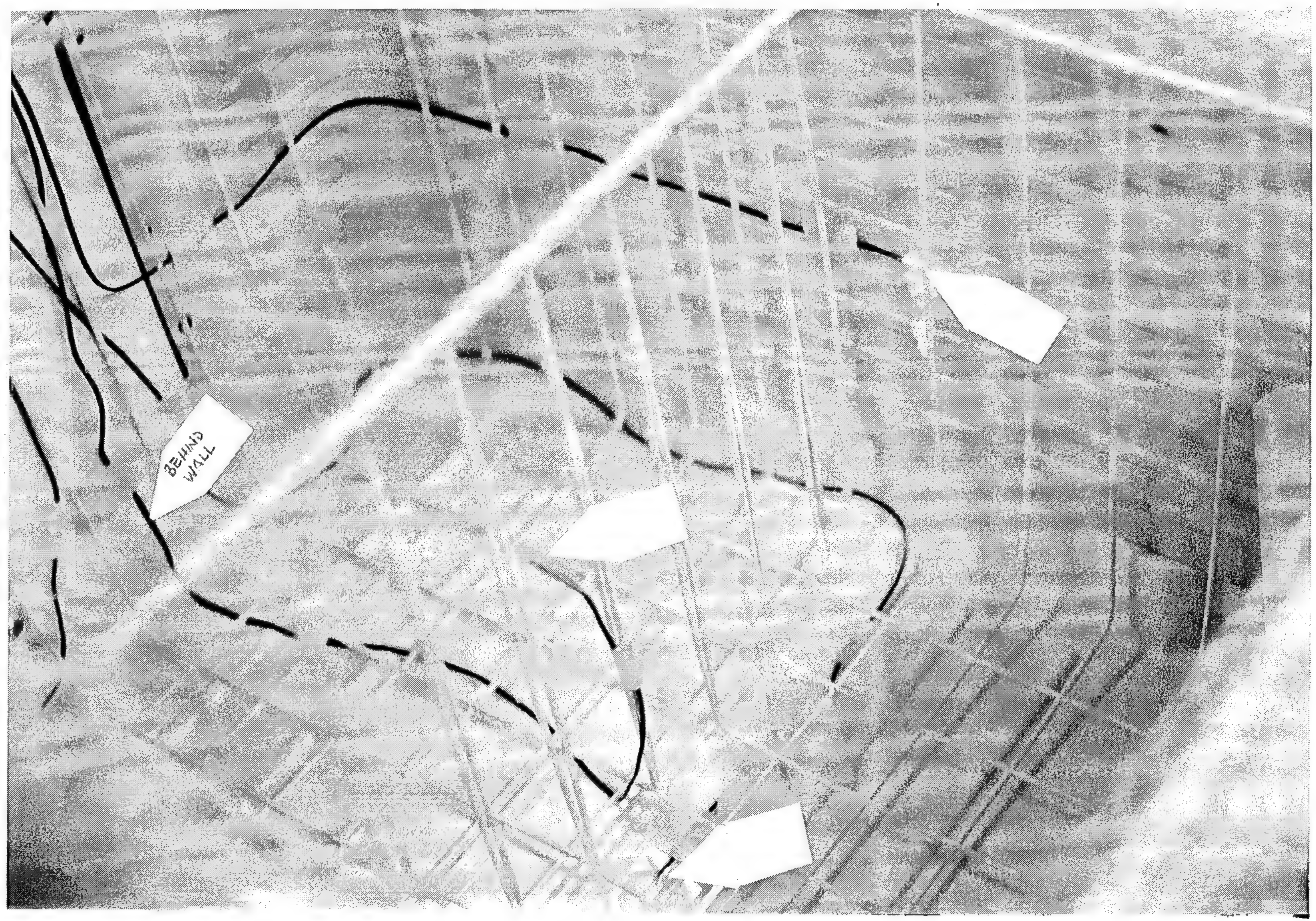

Figure 1. Thermocouple locations inside film cooler.

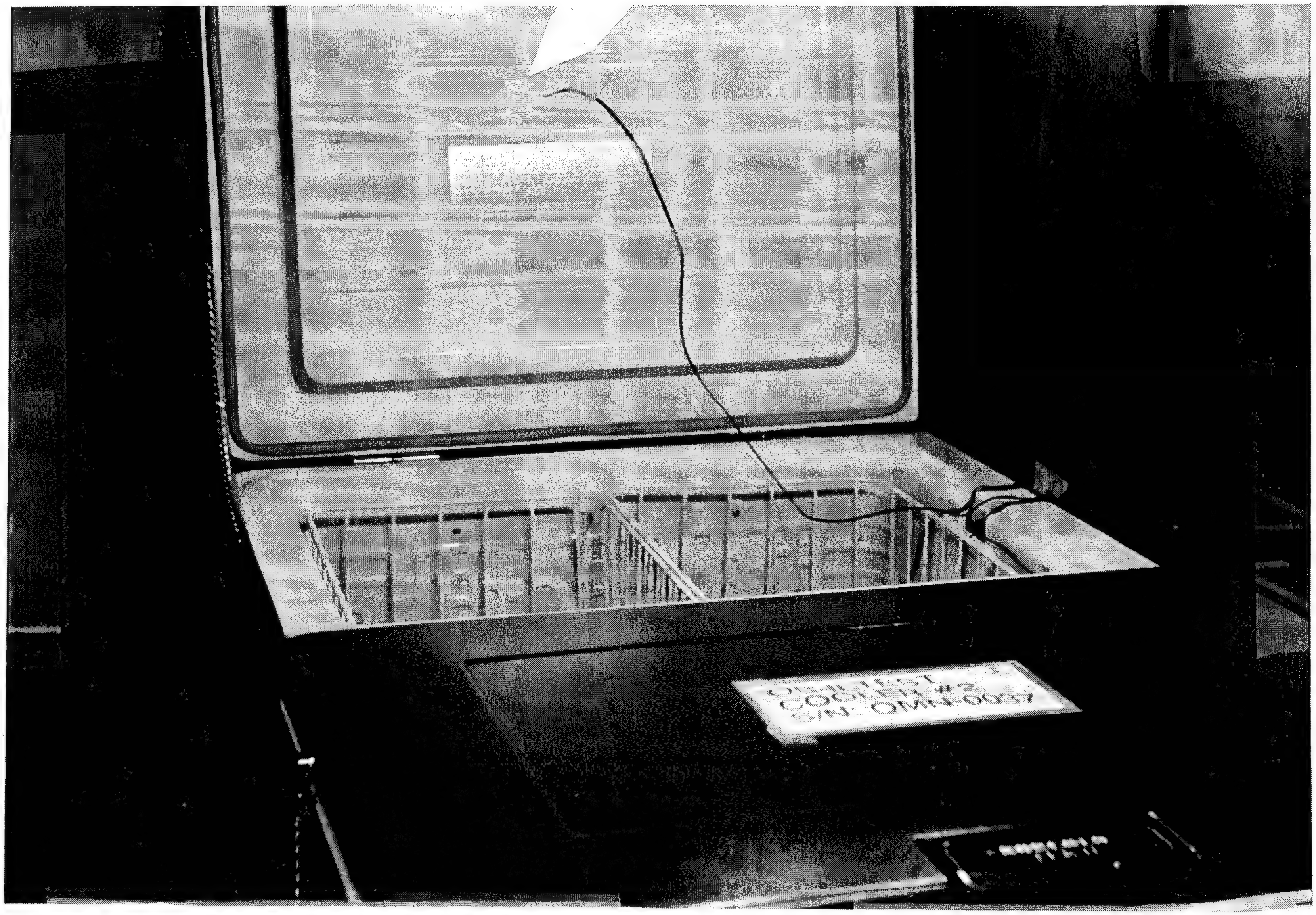

Figure 2. Thermocouple location on inside surface of film cooler lid.

shown in Figure 1 was placed on the cooler back wall, and Figure 2 shows the sixth thermocouple located on the inside surface of the cooler lid. The wall, bottom and lid thermocouples affixed by an adhesive tape such that the thermocouple bead was in contact with the cooler surface. Thermal grease (the white substance evident on the thermocouple beads in Figures 1 and 2) helped ensure that the thermocouple beads maintained sufficient thermal contact with the cooler surface so as to maintain the integrity of the thermocouple measurements. The cooler center thermocouple was attached to the wire baskets inside the coolers to track the approximate air temperature within the cooler. The cooler side thermocouple was also located in the free air, but was placed behind the sheet metal protecting the coolant lines (note arrow in Figure 1). This particular thermocouple was placed in a shielded area where, in actual application, it would not be damaged by materials loaded into and removed from the cooler. A preliminary experiment, Figure 3, determined that the temperature history of the side thermocouple closely matched that of the cooler center thermocouple. Consequently, it was felt that the shielded location chosen for the side thermocouple would be satisfactory in real applications as the site for temperature monitoring and thermostat control. For experiments involving the storage of film containers within the coolers, the wire baskets seen in Figure 1 were removed along with all but the side thermocouple.

The film heater was also instrumented with a total of 15 surface-mounted thermocouples. Figures 4 and 5 show details of some of these thermocouple locations. In order to bond the thermocouples in a fashion that would protect them from possible damage during experimentation, the beads were adhered to the roughened aluminum surface by a high-temperature epoxy as shown in the close-up photograph in Figure 6. The thermocouple beads were first glued onto the aluminum with a rapidly curing adhesive that maintained the thermocouple bead in the correct position while the high-temperature epoxy completed a 24 hour cure time. The adhesive also provided a

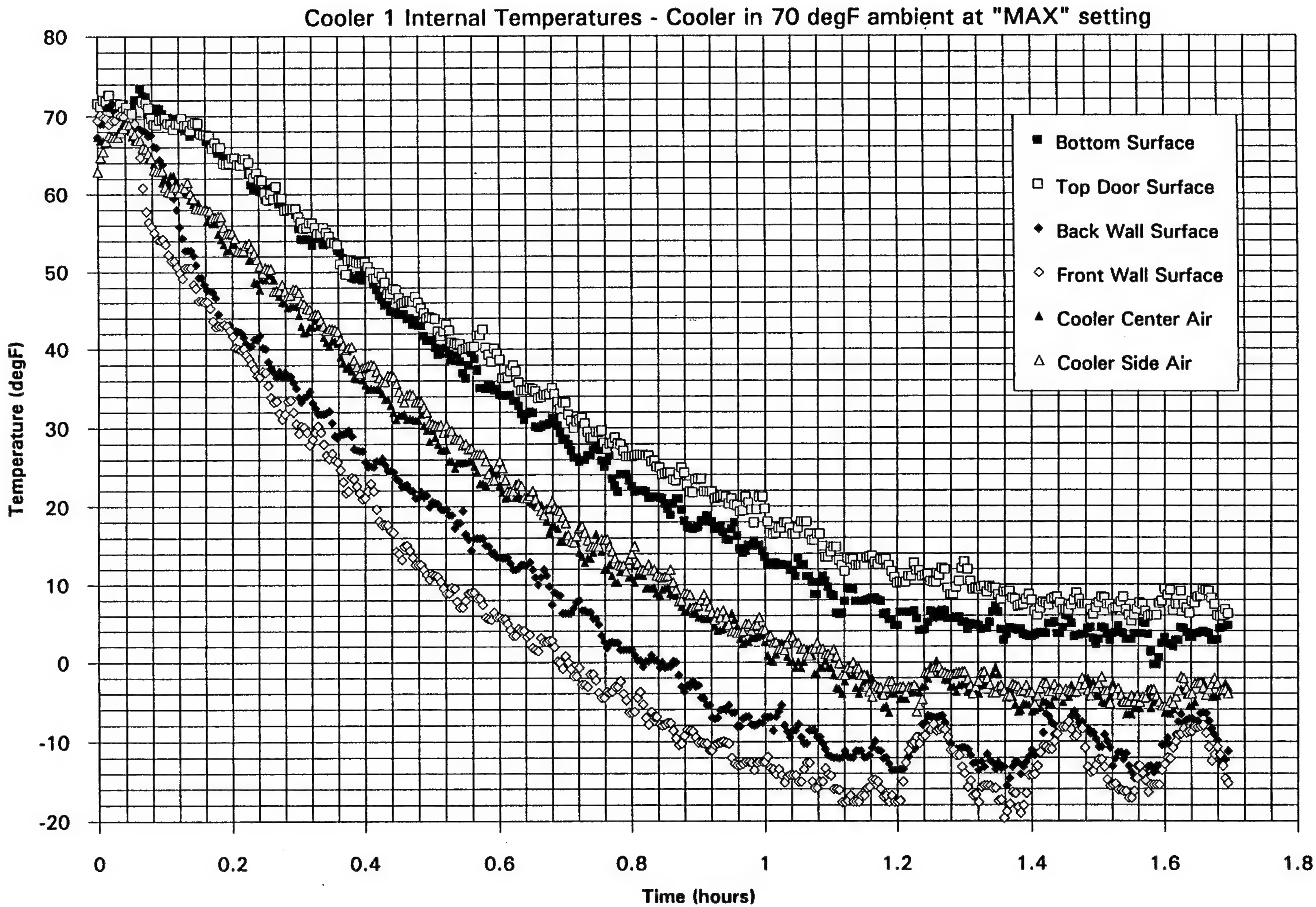

Figure 3. Comparison of Cooler 1 internal temperatures to demonstrate near-equality between internal air temperatures at the cooler center and at the side of the cooler behind the protective evaporator line shield.

very thin layer of electrical insulation between the bead and the surface. The thinness of the layer, however, ensured that the thermal resistance to heat flow to the bead would be minimal, thus ensuring fairly accurate surface temperature measurements. The epoxy not only protected the bead and helped fasten it to the surface, but it also provided increased contact area with the aluminum surface; the thermal mass of the epoxy helped ensure that the thermocouple bead was sensing a correct surface temperature. The film heater schematic detailed in Figure 7 reveals the 15 thermocouple locations.

Four of the 15 thermocouples were dedicated to the temperature controllers. Preliminary tests with the heater revealed the highest film-contacting surface temperatures to be located in the center and bottom of each of the four film trays. Consequently, in order to safeguard against temperatures that could prove damaging to the film or to an operator, these four "hot spots" were chosen as the sites for temperature measurements that would fulfill the thermostat control function. The model number for the microprocessor-based temperature controllers was Omega CN76030. The specified operating ambient temperature range for this particular controller model is 14 to 130 °F (0 to 90% relative humidity), while the storage range is extended to -40 to 175 °F. The temperature controllers were calibrated by the manufacturer.

Figure 5 also shows the pass-through holes cut into the side of the heater for both the heat pad power wires and the thermocouple wires. While the near proximity of the power and thermocouple wires may have introduced additional electrical noise into the thermocouple voltage signals, most of the collected temperature data did not appear to be seriously affected relative to the situation when the heat pads were unpowered. The thermocouple wires inside the heater were temporarily fastened in place with an adhesive aluminum tape.

Figure 4. Thermocouple locations on bottom half of film heater.

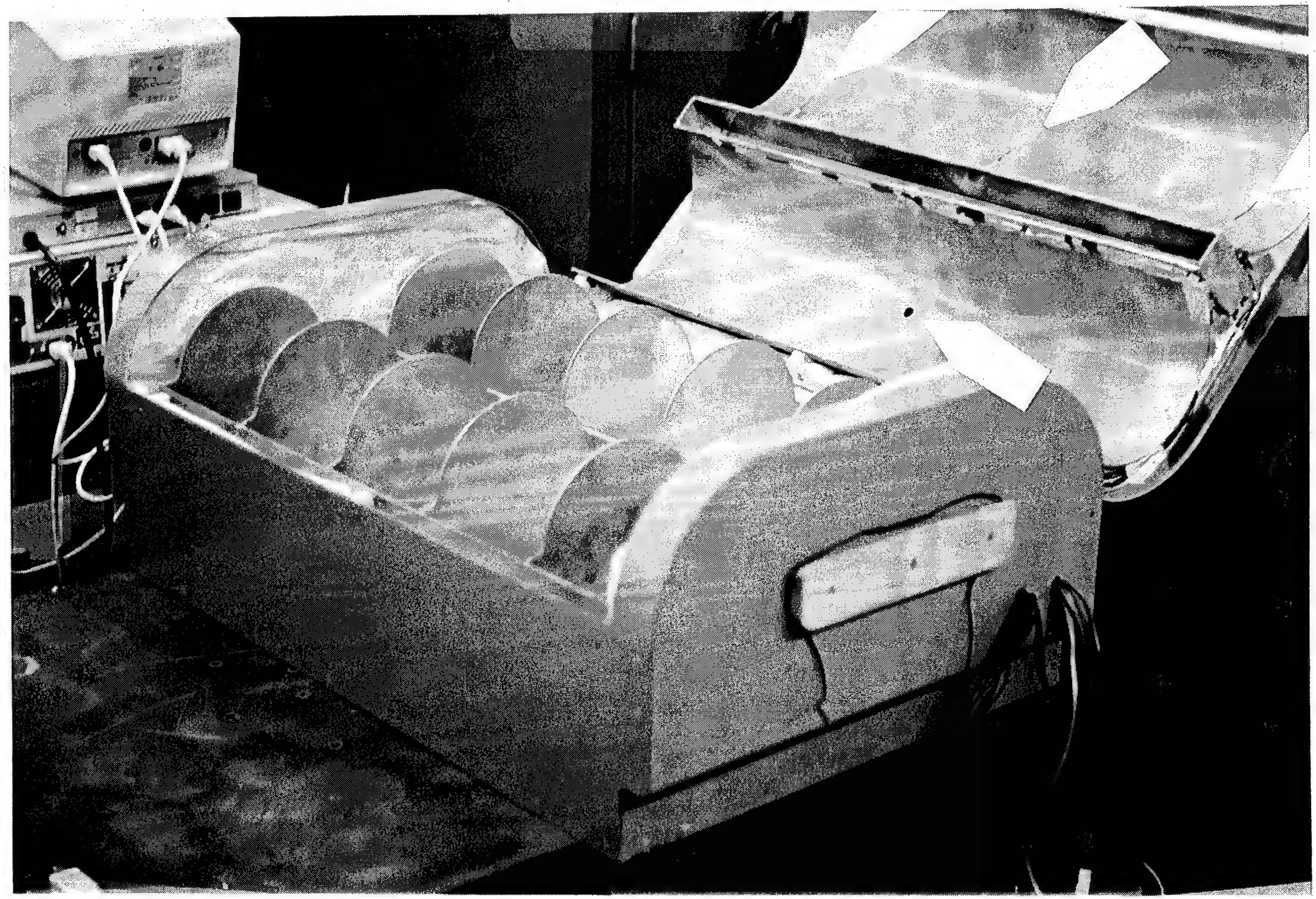

Figure 5. Thermocouple locations on top half of film heater.

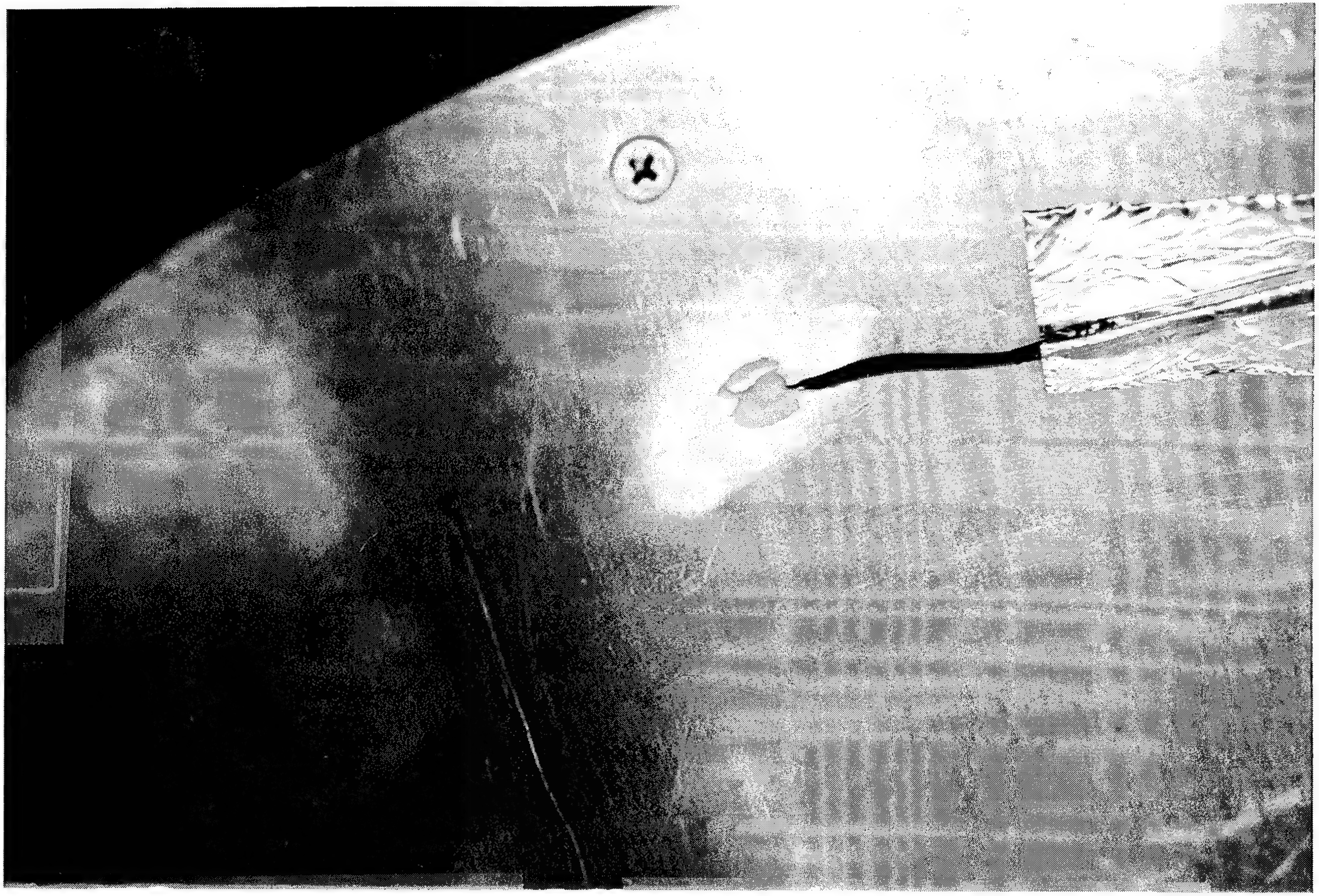

Figure 6. Detail of thermocouple bonding and mounting on film heater aluminum surface.

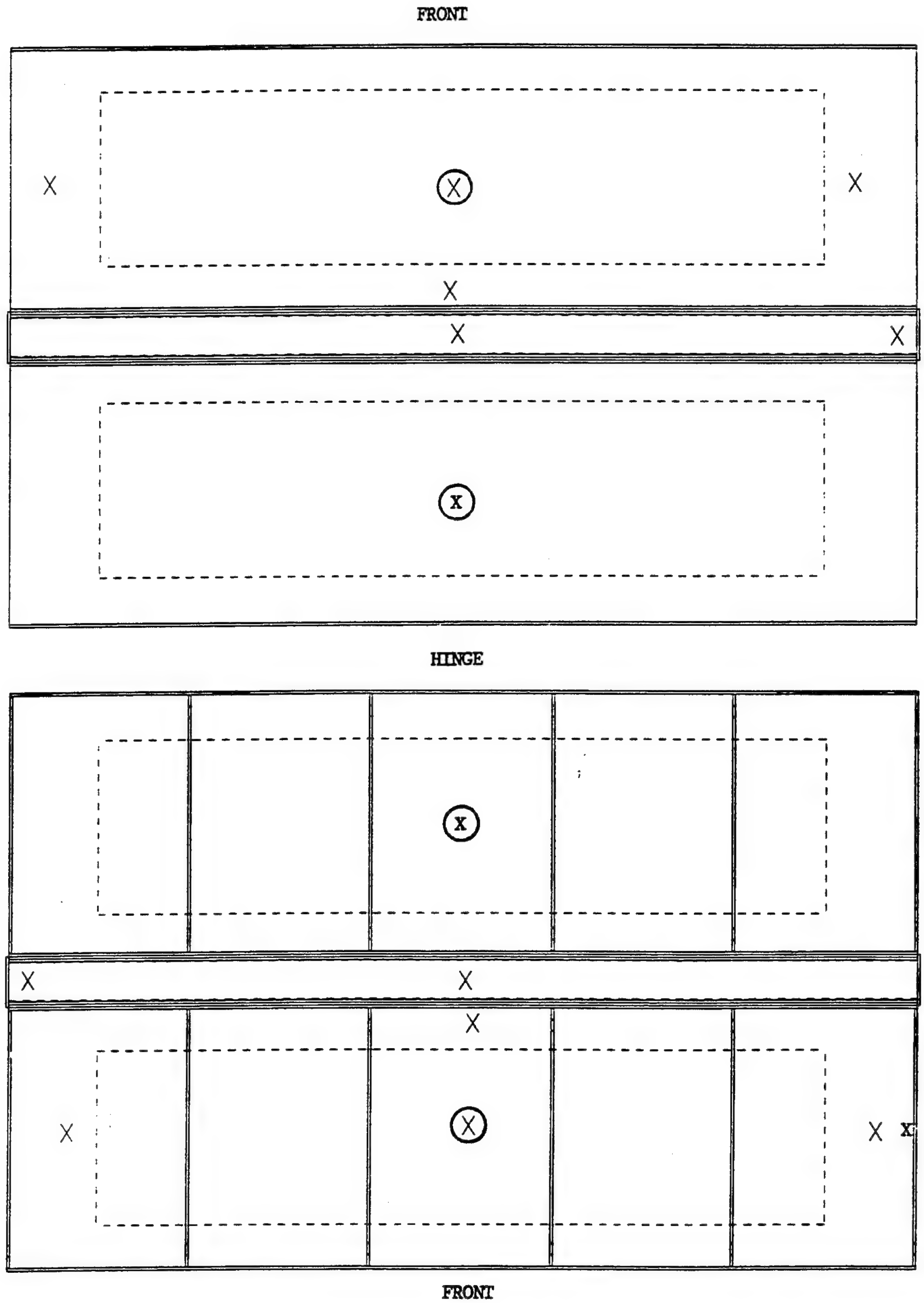

Figure 7. Film heater schematic (top view in open position - upper portion of heater at top of page). Thermocouple locations (X) enclosed by a circle are used by temperature controllers to regulate power to the heater pads (dashed lines).

In order to gauge the temperature within the "core" of the film rolls, both a large (1000 ft) and a small (350 ft) roll were individually wound by NAIC such that a thermocouple could be placed at both a central and a surface location within the rolls. This central location, manifest in Figure 8, was positioned to be approximately one-third of the roll thickness away from the surface of the center spool in order to help approximate an internal film roll temperature. In reality, however, the relatively low thermal conductivity of the plastic film substrate precludes determination of any "average" film roll temperature from the core temperature alone; the temperature profile through the film roll thickness could be quite pronounced, meaning that the difference between the surface and "core" temperatures could be quite high during at least the initial transient stages of film heating/cooling. The surface and core thermocouple locations were chosen to approximate the sites of the fastest- and slowest-responding temperatures, respectively, within a film roll. Determination of an "average" film roll temperature considering both the surface and core temperatures is outlined below. Similarly, the VHS cassette was prepared such that a thermocouple bead was inserted and fastened into a hole drilled radially about two-thirds of the way into the thickness of the video medium.

All thermocouples, including one to monitor the interior ambient temperature of the 33 cubic foot temperature chamber, were wired to a Keithley ViewDAC data acquisition system. The data acquisition program collected temperature information from the T-type thermocouples at regular, predefined time intervals. The resultant ASCII data file was subsequently analyzed using spreadsheet and curve fitting software to satisfy the time/temperature prediction requirements.

2.2 Cooler Tests

Three primary series of experiments investigated the thermal behavior and characteristics of the Norcold Tek II coolers. The first examined the minimum cooler

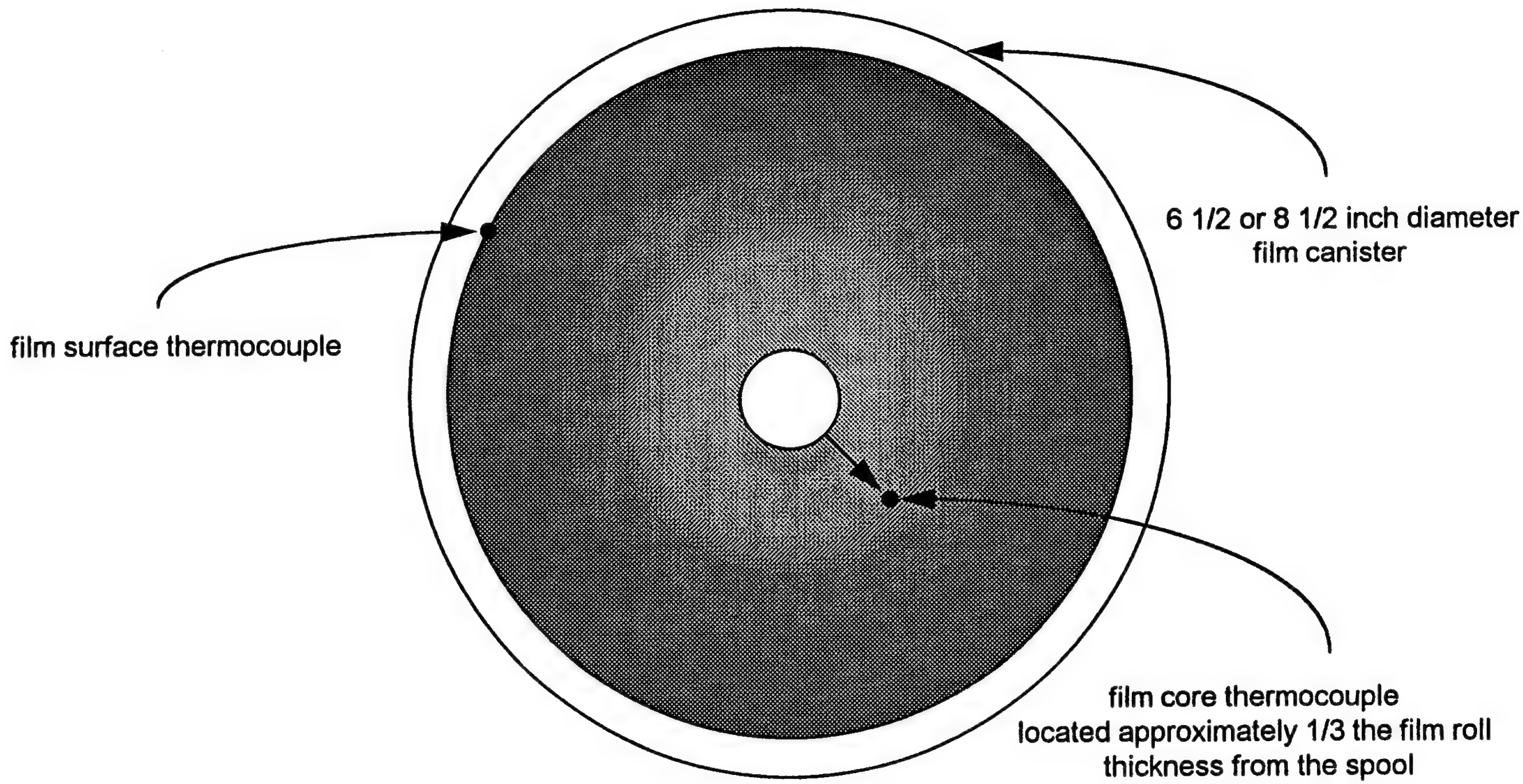

Figure 8. Film (shaded) in film canister with thermocouple locations

internal operating temperature as a function of the external ambient temperature a cooler may be exposed to. The second series involved a cooler loaded with eight large rolls of film; given initial film and ambient temperatures, the cooler was monitored as it cooled the film to a steady-state condition. Finally, the third test sequence, involving different quantities of film loads, required variation of the initial film temperature and ambient temperature to investigate the coolers' ability, when unpowered, to protect the film from extreme hot and cold ambients.

2.2.1 Minimum Cooler Internal Temperature Tests

The efficiency of refrigeration cycles is highly dependent upon the ambient temperature to which the condenser coils are exposed. Because the condenser's purpose is to transfer heat from the coolant in the lines to the ambient air, the condenser's efficiency increases as the temperature difference between the ambient and the coolant coils increases (the ambient temperature being the lower of the two). Consequently, a cooler's ability to remove heat from objects stored within the cooler will decrease as the ambient temperature increases.

The objective of this series of tests was to determine the lowest internal temperature that the cooler could reach as a steady-state condition for a range of specified external ambient temperatures. For these experiments, an open cooler was loaded into the 33 cubic foot temperature chamber and allowed to come into thermal equilibrium with the chamber at the chamber's set point operating temperature. That is, the experiment was not started until the cooler had come to be at the same temperature as the chamber. The progress of the cooler's temperature was monitored, without collecting data, by the data acquisition program. Once thermal equilibrium between the cooler and the chamber had been achieved, the cooler was closed, the chamber was allowed to return to the original set point temperature, and the cooler was turned on at its maximum setting. Data

collection, taken every 15 seconds, began before the cooler was turned on. The chamber set point temperatures projected for examination were 131, 120, 110, 100, 90 and 80 °F.

2.3 Fully-Loaded Cooler: Cooling Capacity Tests

A cooler's ability to cool a large load of film was examined under combinations of different initial film load and external cooler ambient temperatures. Eight large rolls of film were used as the load in this series of tests. One of the eight was the instrumented large roll. The film rolls were stabilized at the desired temperature in the 8 cubic foot chamber, while the closed and sealed cooler, now regulated by a thermostat controller, was set to run at a specified temperature in the 33 cubic foot chamber. The film and large chamber were both initialized at the same temperature to simulate film that had been stored in the environment external to the cooler.

Once the film and cooler had both reached a steady condition at the desired temperatures, the film was loaded into the cooler, the cooler was closed, and data acquisition was initiated. The film temperatures (surface and core) and cooler internal and chamber temperatures were all recorded every 15 seconds until the film reached a steady-state temperature condition.

The operating parameters that were varied in this series of tests were the initial film/chamber temperatures and the cooler set point temperature. The cooler set points were chosen to be 35 °F and 0 °F (regulated by a thermostat which read the cooler internal temperature through the thermocouple located on the side of the cooler cavity behind the coolant line shield). The thermostat controller was set for this series with a 1 °F hysteresis (i.e. with the thermostat set point at 34 °F and a 1 °F hysteresis, the cooler turns on when the internal temperature reaches 35 °F and turns back off when it cools to 34 °F). The three initial film/chamber temperatures for the 35 °F cooler set point were to be 60, 80 °F and the maximum allowable external ambient temperature corresponding to a cooler internal temperature of 35 °F (a temperature to be found from the "Minimum

Cooler Internal Temperature Tests"). Similarly, the one initial film/chamber temperature for the 0 °F cooler set point was to be the maximum allowable external ambient corresponding to a cooler internal temperature of 0 °F. Information regarding temperature combinations other than those tested was to be extrapolated from the collected data.

2.4 Unpowered "Hot/Cold Soak" Tests

The objective of this test series was to simulate conditions where, for example, a cooler's power would be cut off after a day's mission. Realistically, the cooler could then be subject to extreme ambient temperature conditions - hot or cold - that could eventually harm the film if not adequately protected within the cooler. Two coolers were to be involved in these experiments; one cooler would be loaded with eight large film canisters, while the other would contain five small canisters and one VHS cassette in a cassette case. All three of the instrumented film types (large and small rolls and VHS) were employed in this effort.

In order to create a more-or-less typical external ambient that may be found on an aircraft, the 33 cubic foot temperature chamber was set to operate for the first portion of each test in this series at 70 °F. In reality, however, if the internal temperature of an aircraft such as that used in the Open Skies program were to vary by 70 ± 20 °F, the differences in the end results would be negligible. The other experimental parameters were the initial film and cooler set point temperatures as well as the temperature chamber setting for the portion of each test following initialization.

The film was stabilized in the eight cubic foot chamber at the appropriate temperature prior to each experiment. The closed coolers were set to operate at the designated temperature in the 70 °F ambient of the large chamber. After both the film and coolers had come to a steady condition, this being monitored by the data acquisition program, the film was loaded into the coolers and the coolers were closed. Power to the

coolers was subsequently cut off, and the large chamber was reset to the desired temperature for evaluation. The proposed test conditions are detailed in Table 1 below.

Table 1. Test Conditions for "Hot/Cold Soak" Tests

Test No.	Initial Film Temperature	Cooler Set-point Temperature	Chamber Setting
1	35	35	131
2	35	35	90
3	0	0	131
4	80	70*	-67
5	80	70*	-30
6	100	70*	-67

*cooler left open in 70 °F chamber to initialize
(all temperatures in table expressed in °F)

As in other tests, data was to be collected every 15 seconds until the film core temperatures had either reached 100 °F or steady-state (for Tests 1-3), -10 °F or steady-state (for Tests 4-6) or until a maximum time period of 24 hours had been completed.

After an initial analysis of the hot/cold soak experimental data had been made, it was suggested that the coolers' ability to protect the film from extreme ambient temperatures could be enhanced by enclosing the cooler with an insulative blanket. Such a blanket was prepared that enclosed all but the end of the cooler housing the refrigeration system. This end was left exposed to ensure the system would be ventilated for immediate use without having to remove a separate portion of the insulative cover. While only one blanket was manufactured, it was felt, based upon the results of the initial test series, that sufficient data could be collected with one cooler and a more limited test sequence (the limitation being the number of tests performed separately for each of the two film load quantities). Six tests, three with a large film load (eight large film canisters) and three with a small load (five small canisters and one VHS cassette), were

conducted as detailed in Table 2.

Table 2. Test Conditions for "Hot/Cold Soak" Tests with Insulating Thermal Blanket on Cooler

Size of Film Load	Initial Film Temperature	Cooler Set-point Temperature	Chamber Setting
Large	0	0	131
Large	35	35	131
Large	100	70*	-67
Small	0	0	131
Small	35	35	131
Small	80	70*	-30

*cooler left open in 70 °F chamber to initialize
(all temperatures in table expressed in °F)

2.5 General Considerations

In all of the cooler tests, a "steady-state" condition was defined to be temperature changes of no more than 2.0 °C (3.6 °F) per hour. In addition, the highly convective (forced air) nature of the temperature chambers needs to be discussed in order that the implications of convection upon the experimental results may be understood. Generally speaking, as the velocity and turbulence of a fluid, such as the air within the temperature chamber, are increased, the heat transfer coefficient associated with the fluid motion is likewise increased proportionately. As a consequence, the rate of heat transfer from an object placed in a more convective environment will be greater than that from the object in otherwise identical conditions save the level of convective heat transfer.

Thus, the "hot/cold soak" test series will generate data that reflects larger heat transfer rates than would be seen in the case of an ambient of more-or-less quiescent air. In other words, the data from this third series will show the film to heat or cool, depending on the test conditions, somewhat faster than what may actually occur in otherwise identical conditions on an aircraft.

In a similar fashion, the first two series of cooler tests will also be affected by the convection in the chamber. Large convective heat transfer rates in these tests may slightly enhance the coolers' performance; a principle factor governing the coolers' ability to remove heat from internal loads is the external ambient condition. If convection heat transfer from the condenser coils is increased by forcing air across the coils, then the cooler may be able to cool the film load slightly faster than if the air surrounding the condenser coils is stagnant. According to the manufacturer's technicians, however, if the coolers are situated such that the condenser coils have adequate ventilation and exposure to conditioned ambient air, the coolers' performance should closely match the experimental results. In addition, the manufacturer's technicians felt that the level of relative humidity should have little effect upon the coolers' performance.

In an attempt to foster conservative temperature predictions for both the "Fully-Loaded Cooler: Cooling Capacity Tests" and the "Unpowered 'Hot/Cold Soak' Tests" involving large film canisters, the large film canister instrumented with surface and core thermocouples was strategically located within the cooler. The large canisters were placed into the cooler in two layers of four canisters each. The instrumented canister was placed on the top layer next to the portion of the evaporator lines nearest their point of exit from the cooler's internal volume (the back, right-hand corner of the cooler when viewed from the front). This location was chosen as one that could be representative of the warmest, and, thus, the most conservative, site within the cooler.

2.6 Film Heater Tests

It was desired to examine the film heater's capabilities to warm film in half-full, completely full, and half-full/partially-inoperative conditions. The half-full film load consisted of four large film canisters, one small canister and two VHS cassettes in protective cases. The completely full test condition required eight large canisters, two small canisters and three VHS cassettes. The half-full/partially-inoperative experiment involved a film load identical to that of the half-full test and required that the bottom back heater pad be unpowered during the experiment. The objective of this latter test was to simulate the possibility of a heater pad failure during the course of a mission. While the original project plan called for the test parameters as explained below and film loading as detailed in Figures 9-10, the results of such dictated deviations from the original plan that are explained in the **Heater Tests** paragraphs of the **Results and Discussion section.**

2.6.1 Heater Half-Full Test Sequence

The original test project plan called out for 12 individual tests in this sequence. The first six tests required that the thermostats controlling the temperature of the heater pads be set at 110 °F. The other conditions stipulated for the first six tests are detailed in Table 3.

Table 3. Test Conditions for Half-full Heater Tests

Test No.	Initial Film Temperature	Chamber Setting
1	-10	-67
2	-10	-30
3	-10	0
4	30	-67
5	30	-30
6	30	0

(all temperatures in table expressed in °F)

The test conditions for the second set of six tests were identical to those presented in Table 3 with the exception that the thermostats were set at 70 °F.

The film was initialized in the small temperature chamber prior to each test. Likewise, the heater was initialized by leaving the lid open and the interior of the heater exposed within the operating large chamber. Consequently, the heater was at the ambient temperature at the start of each test. Once the film temperatures had stabilized, the film was transferred to the heater, all electrical connections were made, the heater was closed, data acquisition was begun, and the heater power was turned on. Each test was monitored with 15 second intervals between data points until the film had reached a steady-state condition (as defined above in General Considerations).

In order to reduce the electrical noise seen in the signals of some of the thermocouples affixed to the heater surfaces, the heater was placed on two wooden blocks. While this provided electrical insulation, the act of raising the heater off the surface of the chamber floor exposed the bottom of the heater to air currents within the chamber, thus increasing the surface area of the heater exposed to the ambient temperature. This situation was recognized and corrected in experiments described below. The film was loaded into the heater in the pattern depicted in Figure 9.

2.6.2 Heater Completely Full Test Sequence

Two additional tests were conducted with the heater to provide a relative comparison between a heater in a half-full condition and a heater fully loaded with film. The test conditions for these two tests both required a thermostat set point of 110 °F and an ambient of -30 °F. The initial film temperatures were -10 °F and 30 °F, respectively, for the two tests. The film and heater/chamber initialization was conducted as described above for the half-full test sequence. The film loading pattern is detailed in Figure 10.

2.6.3 Heater Half-full but Partially Inoperative

To simulate the heater's performance with one of the heater pads being inoperative, the power to the back bottom heater pad was interrupted during the two tests called for in this sequence. Test conditions for the two tests specified a thermostat set point of 110 °F and an ambient of -30 °F, while the initial film temperatures were -10 °F and 30 °F, respectively. The film loading pattern, as initially specified in the project plan, required all the film (four large canisters and one small canister), to be loaded in the back film tray. However, later consideration suggested the more realistic situation would be to load all the film into the front tray where the heater pad was still functional. This consideration assumed such a strategy would be followed by an operator cognizant of the back film tray's power loss. Both situations were tested, the second being done with the thermal blanket discussed below, placing the small film canister in the center slot of the five slots designated in a film tray. The large film canisters were placed in the other four slots, and the VHS cassettes were located as before in the cavity between front and back film trays.

2.7 Film Stabilization Tests

To predict the thermal behavior of individual film canisters exposed to particular ambient temperatures, the three instrumented film types (large roll, small roll and VHS cassette) were loaded into the small temperature chamber and allowed to stabilize to an initial test condition (either 0, 35 or 55 °F). Following stabilization at the initial temperature, the canisters were covered by a rack and plastic sheet, as shown in Figure 11. The rack and plastic were installed prior to starting the data acquisition portion of the experiment in order to minimize the convective effects within the chamber and to approximate the actual conditions (quiescent ambient air) the film might see aboard the aircraft. Each initial film temperature condition was tested at

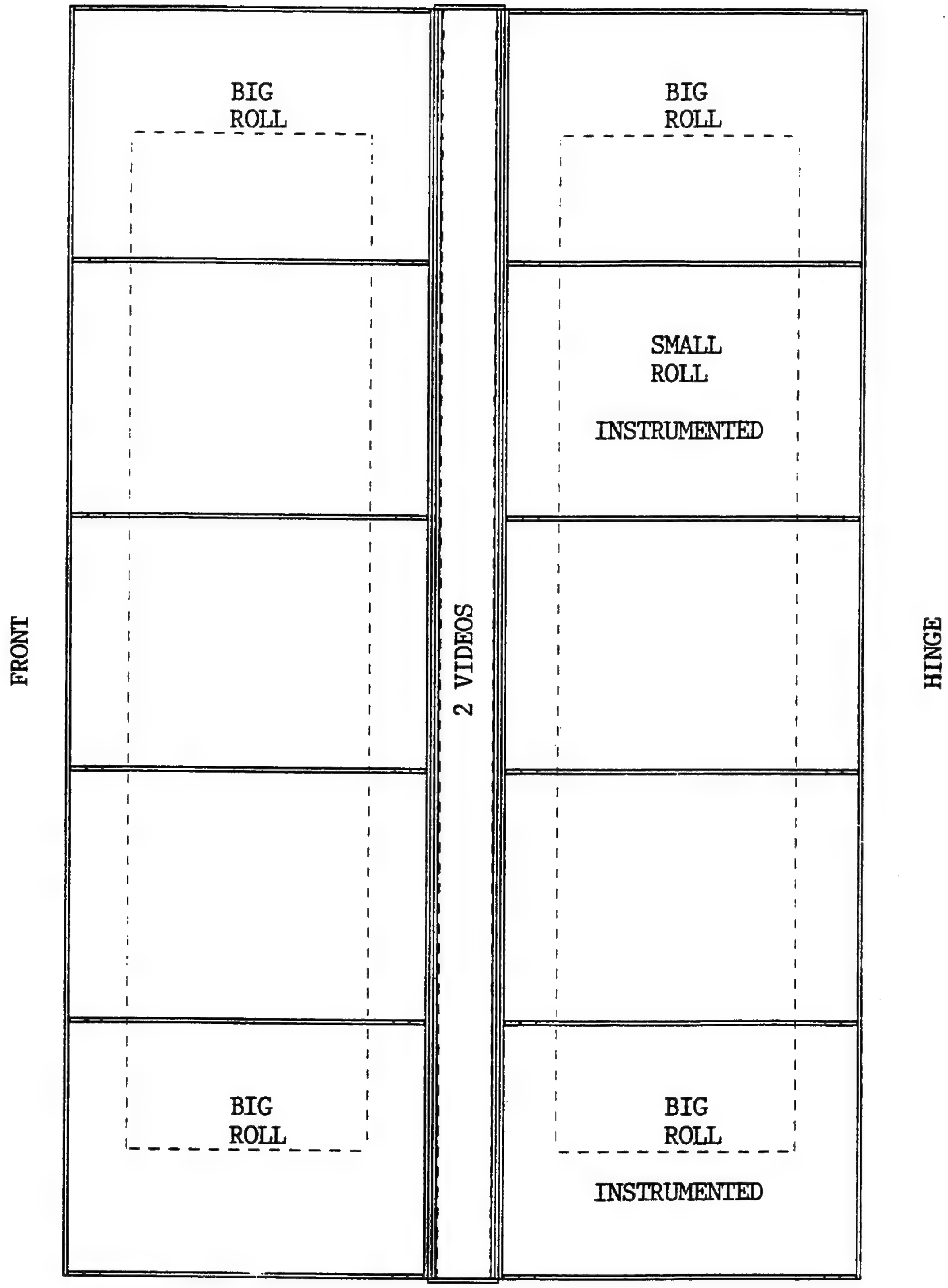

Figure 9. Film loading pattern for half-full heater test sequence. Dashed lines represent heater pads.

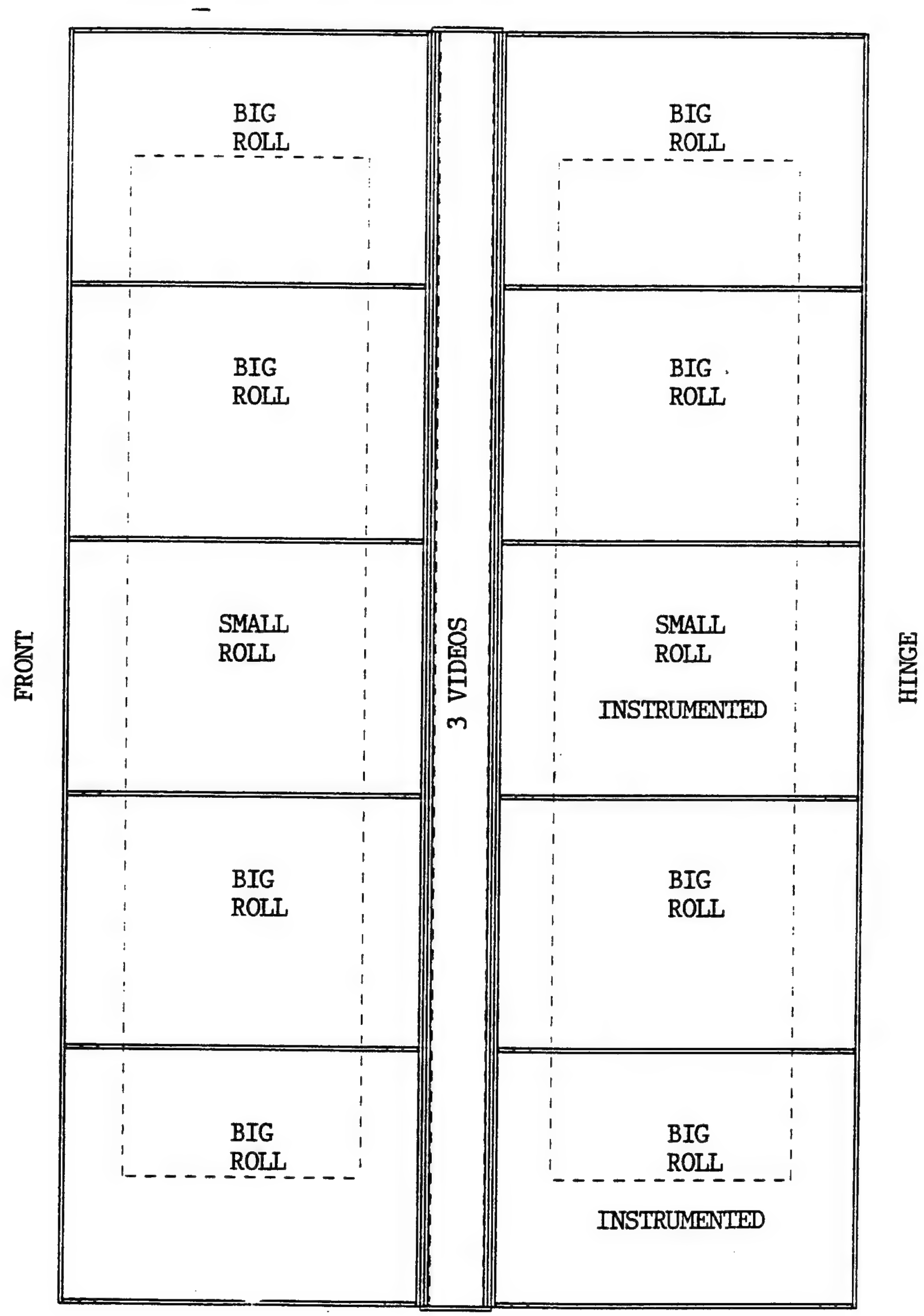

Figure 10. Film loading pattern for completely-full heater test. Dashed lines represent heater pads.

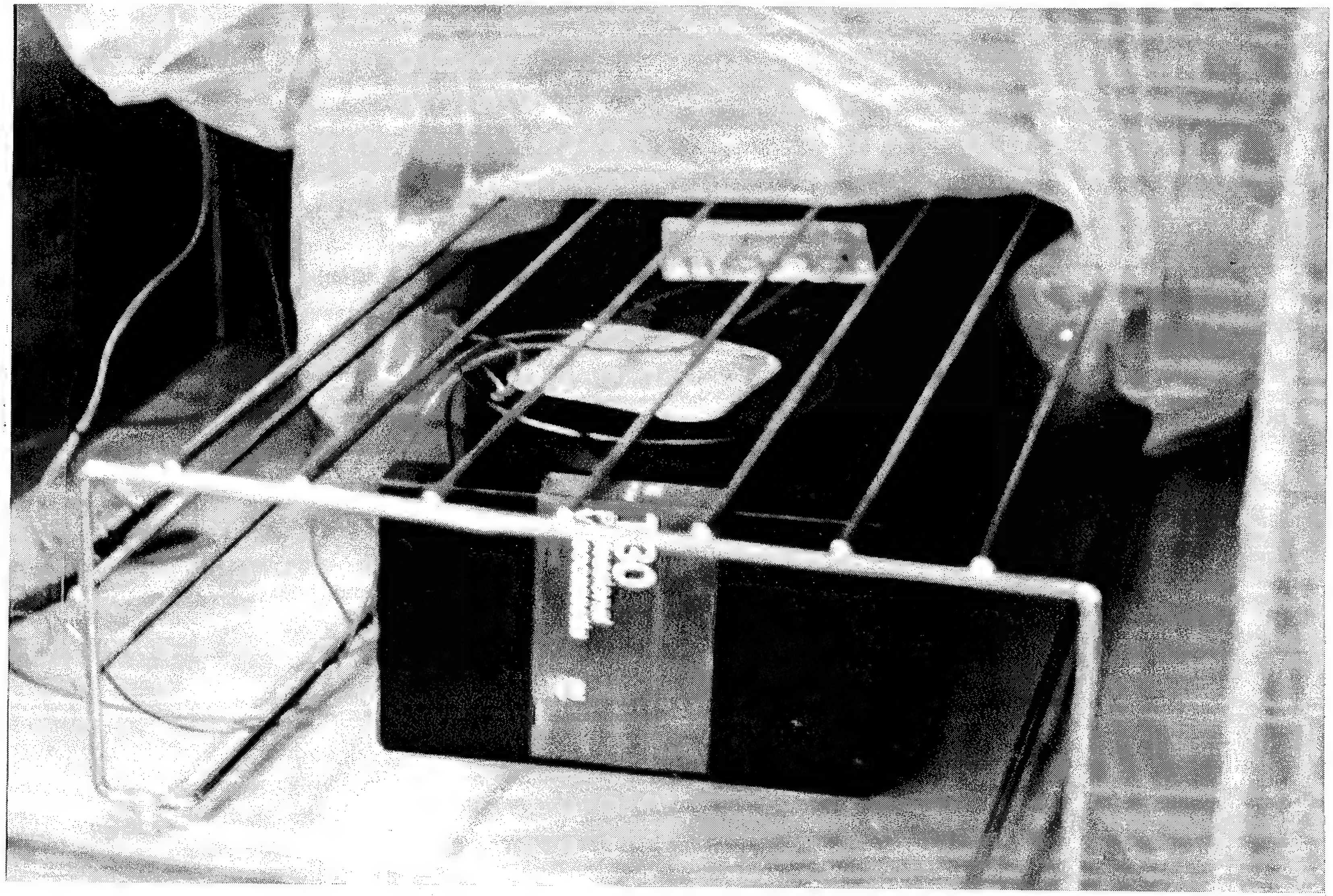

Figure 11. Film situated inside small temperature chamber for film stabilization tests - note the rack and plastic sheeting used to minimize convection heat transfer.

both 90 and 131 °F ambients. Data taken every 15 seconds was collected until all film canisters had reached a steady-state condition.

3.0 RESULTS AND DISCUSSION

In order to predict time and temperature data for a wide variety of initial and test conditions, most of the data accumulated during this study was modeled with a transition equation of the form

$$T = a + \frac{b}{1 + \left(\frac{t}{c}\right)^{d}} \tag{1}$$

where T is temperature in degrees Fahrenheit, t represents time in hours, a and b are representative of the test conditions, and c and d are constants specific to the thermal characteristics of a particular system. For example, a may represent the set point temperature of the cooler or the initial film temperature and b the difference between the initial film temperature and the cooler set point temperature or the difference between the ambient and the initial film temperatures. The constants c and d affect the shape and curvature of the time/temperature curve. While values of a and b are essentially generic in application to all three film types, c and d prove to be specific to the film type in question.

In addition, in order to provide a better approximation to an "average" or "bulk" film temperature other than that indicated by the core temperature, a procedure was devised to use both the surface and core temperatures to produce a temperature more representative of the whole of the film roll. The development of the procedure is outlined in Appendix A of this report, and the key expression to determine the average temperature is

$$T_{bulk} = \frac{2}{3}T_c + \frac{1}{3}T_s \quad . \tag{2}$$

T_{bulk} represents the average or bulk film temperature, and T_c and T_s represent the core and surface temperatures, respectively. As a result of the error associated with the thermocouple measurements and the procedure followed to predict the time/temperature data, it is estimated that the error in the tabulated predictions is approximately ±5 °F.

3.1 Cooler Tests

3.1.1 Minimum Cooler Internal Temperature Tests

In order to expedite the testing procedure, both Coolers 1 and 2 were loaded into the temperature chamber for the initial tests of this series (see Figure 2). In addition to the temperature data collected by the data acquisition program, the chamber's temperature history was recorded by a dedicated circular chart recorder. The circular charts proved useful to note problems associated with the heating/cooling cycles of the chamber; any fluctuations in the chamber temperature could thus be referenced to possible perturbations in the cooling processes of the film coolers.

The minimum internal temperatures of Coolers 1 and 2 were evaluated at ambient temperatures of 67 (sitting in room ambient), 80, 90, 100, 110, 115, 120, and 131 °F. With the exception of the test results at an ambient of 131 °F, the minimum temperatures and the approximate times required to achieve these temperatures are displayed in Figure 12. The minimum internal temperatures of Coolers 1 and 2 were approximately equal through the temperature ranged evaluated between 67 and 110 °F. However, the experimental results at 115 °F are vastly different. It is believed that the difference in the minimum internal temperature is a function of the operating characteristics of the refrigeration cycles; the refrigerant charge within each system is probably slightly different, and consequently, the cooling performance near the limit of

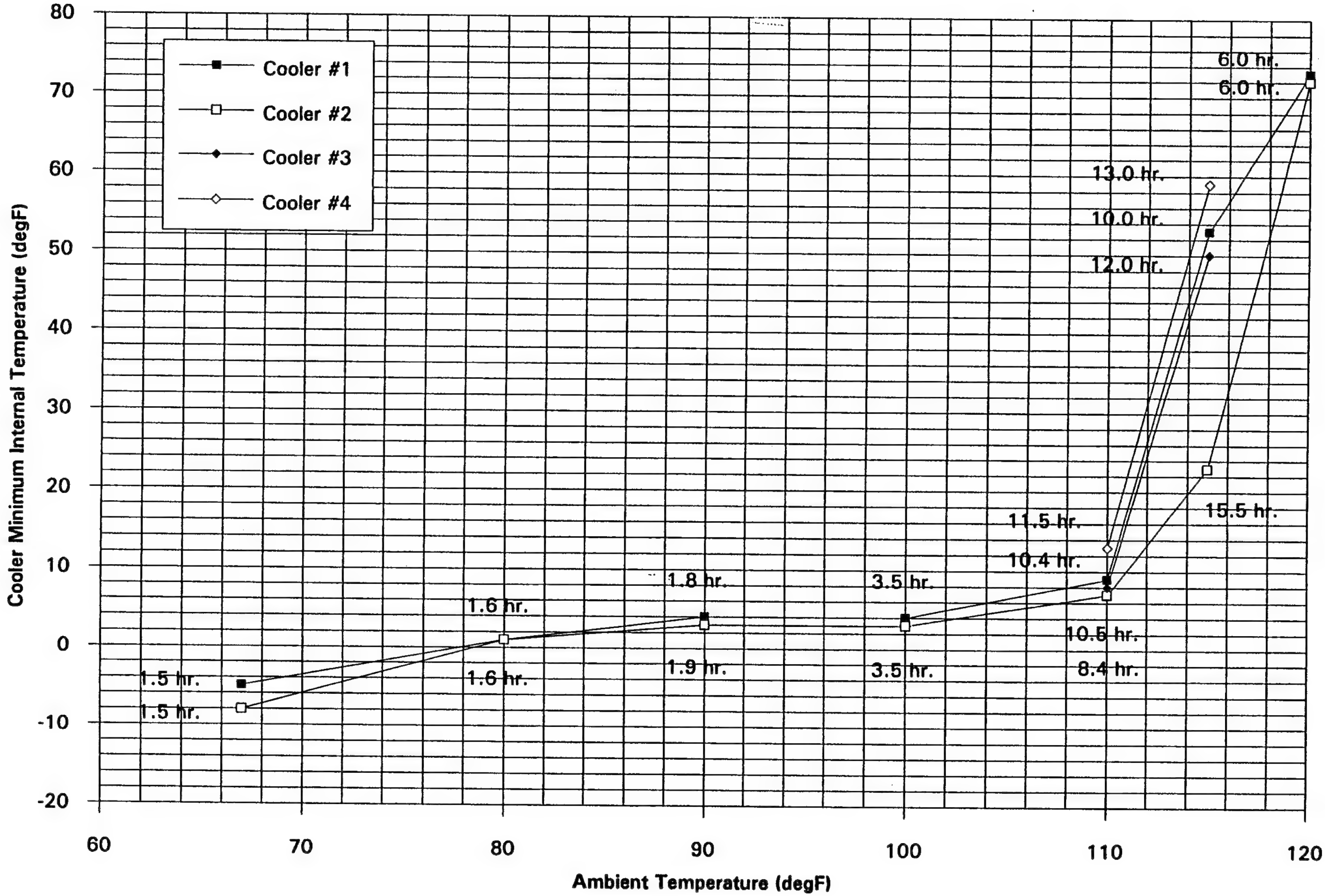

Figure 12. Cooler minimum internal temperature as a function of ambient temperature (all coolers empty during tests).

acceptable operation varies between systems. The results at 120 °F show the cooling performances to be approximately equal. Likewise, while not plotted in Figure 12, the minimum internal temperatures of Coolers 1 and 2 in an ambient of 131 °F were both near 110 °F.

To determine which of Coolers 1 and 2 was more characteristic of an "average" cooler performance, the minimum internal temperatures of Coolers 3 and 4 were evaluated at both 110 and 115 °F. The results, also shown in Figure 12, suggest that Cooler 1 demonstrates a level of performance representative of the majority of this type of cooling unit. The information produced by these minimum internal temperature tests was used to determine some of the ambient temperature levels for experiments discussed in the following section.

3.1.2 Fully-Loaded Cooler: Cooling Capacity Tests

The intent of the acquisition of temperature/time data from the experiments in this test series was to ultimately provide charts useful to a mission crew for purposes of cooling large quantities of film under various temperature conditions. After completion of the tests proposed in the initial project plan, as discussed above in the section on "Methods," two additional experiments were conducted in order to solidify the prediction and extrapolation of data for conditions other than those tested. The additional test conditions were (1) a 100 °F initial film and chamber temperature coupled with a 35 °F cooler setting as well as (2) a 50 °F initial film and chamber temperature coupled with a 0 °F cooler setting.

The predicted time/temperature data that has been extracted for this test series from the experimental data is presented in Tables 4-6. These tables present the progress with incrementing time of the average temperature of a large film roll as a function of the external ambient/initial film temperature and the cooler set point (Tables 4-6 represent cooler set points of 0, 20 and 35 °F, respectively).

Table 4. Large film roll average temperature predictions - film **cooled** within a fully loaded (eight large cannisters) Norcold cooler set to operate at **0 °F** (5 in. × 1000 ft Kodak SO-050 and Sp-884 film)

External Ambient / Initial Film Temperature ↓ **Film Temperature (°F)**

80	77	73	67	61	56	51	46	42	38	35	32	30	28	26	24	23	21	20	19	18	17	17	16	15
75	72	67	62	56	51	46	41	38	34	31	29	27	25	23	22	20	19	18	17	16	15	15	14	14
70	67	62	57	51	46	41	37	34	31	28	26	24	22	21	19	18	17	16	15	15	14	13	13	12
65	62	57	52	47	42	37	34	30	28	25	23	21	20	19	17	16	15	15	14	13	13	12	12	11
60	57	53	47	42	38	34	30	28	25	23	21	19	18	17	16	15	14	13	13	12	11	11	11	10
55	52	48	43	39	34	31	27	25	23	21	19	18	16	15	14	13	13	12	12	11	11	10	10	9
50	48	44	39	35	31	28	25	22	20	19	17	16	15	14	13	12	12	11	11	10	10	9	9	9
45	43	39	35	31	28	25	22	20	18	17	15	14	13	13	12	11	11	10	10	9	9	9	8	8
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTES:

1. The surface temperature may be as much as 10 °F colder than the core temperature, but it generally leads the core temperature by approximately 6 to 8 °F.

2. These predicted time/temperature relationships are valid only in the situation tested (a cooler set at 0 °F and loaded with eight large cannisters). Coolers loaded with less film or set to operate at lower temperatures (minimum cooler internal temperature limited to 0 °F at an external ambient of approximately 80 °F) will cool film more rapidly than reflected in the situation above. Likewise, film added to a cooler already partially full with cool film should cool faster than predicted here.

Table 5. Large film roll average temperature predictions - film **cooled** within a fully loaded (eight large cannisters) Norcold cooler set to operate at **20 °F** (5 in. × 1000 ft Kodak SO-050 and Sp-884 film)

External Ambient / Initial Film Temperature ↓ **Film Temperature (°F)**

110	109	107	104	101	98	95	91	88	85	82	79	76	73	70	68	65	63	61	59	58	56	54	53	51
105	103	101	97	93	88	84	80	76	73	69	66	63	60	58	55	53	51	50	48	46	45	44	43	41
100	98	94	90	85	80	75	71	67	63	60	57	54	51	49	47	45	44	42	41	40	39	37	37	36
95	93	88	83	78	73	68	63	59	56	53	50	47	45	43	42	40	39	37	36	35	34	33	33	32
90	87	82	77	71	66	61	57	53	50	47	45	43	41	39	37	36	35	34	33	32	31	31	30	29
85	82	77	71	66	60	56	52	48	45	43	41	39	37	36	34	33	32	31	31	30	29	29	28	28
80	77	72	66	60	56	51	48	44	42	39	37	36	34	33	32	31	30	29	29	28	28	27	27	26
75	72	67	61	56	51	47	44	41	39	37	35	33	32	31	30	29	29	28	27	27	26	26	26	25
70	67	62	57	52	47	44	41	38	36	34	33	31	30	29	29	28	27	27	26	26	25	25	25	24
65	62	57	52	48	44	40	38	36	34	32	31	30	29	28	27	27	26	26	25	25	25	24	24	24
60	57	53	48	44	41	38	35	33	32	30	29	28	27	27	26	26	25	25	24	24	24	24	23	23
55	53	48	44	41	38	35	33	31	30	29	28	27	26	26	25	25	24	24	24	23	23	23	23	23
50	48	44	41	37	35	33	31	29	28	27	26	26	25	25	24	24	24	23	23	23	23	22	22	22
45	43	40	37	34	32	30	29	28	27	26	25	25	24	24	23	23	23	23	22	22	22	22	22	22
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTES:

1. It is estimated from the experimental results that the surface temperature will generally be approximately 6 °F colder than the core temperature.

2. These predicted time/temperature relationships are valid only in the situation tested (a cooler set at 20 °F and loaded with eight large cannisters). Coolers loaded with less film or set to operate at lower temperatures (minimum cooler internal temperature approximately limited to 20 °F at near 110 °F external ambient) will cool film more rapidly than reflected in the situation above. Likewise, film added to a cooler already partially full with cool film should cool faster than predicted here.

Table 6. Large film roll average temperature predictions - film **cooled** within a fully loaded (eight large cannisters) Norcold cooler set to operate at **35 °F** (5 in. × 1000 ft Kodak SO-050 and Sp-884 film)

External Ambient / Initial Film Temperature ↓ **Film Temperature (°F)**

110	109	106	103	100	97	93	90	86	83	80	77	75	72	70	68	66	65	63	61	60	59	58	56	55
105	103	100	96	91	87	83	79	75	72	69	67	64	62	60	58	57	55	54	53	52	51	50	49	48
100	98	94	89	84	79	75	71	67	64	62	59	57	55	54	52	51	50	49	48	47	46	46	45	44
95	92	88	82	77	72	68	64	61	58	56	54	52	51	49	48	47	46	45	45	44	43	43	42	42
90	87	82	76	71	67	63	59	56	54	52	50	49	47	46	45	45	44	43	43	42	42	41	41	40
85	82	77	71	66	62	58	55	53	51	49	47	46	45	44	43	43	42	41	41	41	40	40	40	39
80	77	72	66	62	58	54	52	50	48	46	45	44	43	42	42	41	41	40	40	39	39	39	39	38
75	72	67	62	58	54	51	49	47	46	44	43	42	42	41	40	40	40	39	39	39	38	38	38	38
70	67	62	58	54	51	48	47	45	44	43	42	41	40	40	39	39	39	38	38	38	38	38	37	37
65	62	58	54	51	48	46	44	43	42	41	40	40	39	39	39	38	38	38	38	37	37	37	37	37
60	58	54	51	48	46	44	43	41	41	40	39	39	38	38	38	38	37	37	37	37	37	37	37	36
55	53	50	47	45	43	42	41	40	39	39	38	38	38	37	37	37	37	37	37	36	36	36	36	36
50	48	46	44	42	41	40	39	39	38	38	37	37	37	37	37	36	36	36	36	36	36	36	36	36
45	44	42	41	40	39	38	38	37	37	37	37	36	36	36	36	36	36	36	36	36	36	36	36	36
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTES:

1. It is estimated from the experimental results that the surface temperature will generally be approximately 4 °F colder than the core temperature.

2. These predicted time/temperature relationships are valid only in the situation tested (a cooler set at 35 °F and loaded with eight large cannisters). Coolers loaded with less film or set to operate at lower temperatures (minimum cooler internal temperature approximately limited to 35 °F at near 110 °F external ambient) will cool film more rapidly than reflected in the situation above. Likewise, film added to a cooler already partially full with cool film should cool faster than predicted here.

In addition, the tables note the tabulated predictions are quite specific to a particular combination of parameters. The maximum external ambient/initial film temperature in the tables, for example, was limited approximately to the maximum external ambient temperature in which the cooler could achieve the internal temperature indicated in the tables as the set point temperature. Likewise, the temperature predictions reflect the actual experimental conditions - a cooler fully loaded with eight large film rolls. A reduction in the total film mass in the cooler will decrease the amount of time required to cool the film. Similarly, a cooler already partially full with cool film will be able to cool additional film more rapidly than predicted in the tables. Without additional data for different film loads, however, quantitative statements regarding a percent decrease in cooling time cannot be made. The tables also note the approximate temperature differences measured between the film core and surface during the experiments.

As a consequence of the error associated with the experimental hardware and the data analysis procedure, the data presented in Tables 5 and 6 for the higher external ambient temperatures would lead the reader to believe that the 35 °F set point can cool the film slightly faster during the first few hours than can the 20 °F set point. While this situation obviously does not reflect reality, it is felt that the temperature predictions are correct within the bounds of the associated error. In addition, difficulties in evaluating the coolers' minimum operating temperature at high ambient temperatures (near and above 110 °F) are evident in Figure 12.

3.1.3 Unpowered "Hot/Cold Soak" Tests

The test procedure was initially followed as explained previously; after proper temperature initialization, the large canisters were placed in two layers of four in one cooler, and the five small canisters and the VHS cassette (located between canisters near the center of the cooler) were placed on the bottom of the second cooler without any

stacking of canisters. However, with the addition of a thermal insulating blanket to slow heat loss/gain during the soak tests, only one cooler was used for the experiments as outlined in Table 2.

The "cold soak" results (average temperature changing with time) for the large film roll are presented in Tables 7-10 for ambient temperatures of -14, -30, -45 and -67 °F, respectively, while the large film roll "hot soak" predictions are listed in Tables 11-13. Likewise, the cold and hot soak predictions for the small film roll are presented in Tables 14-20. The "hot soak" ambients are 90, 110, and 131 °F, respectively. Footnotes in the tables explain the specific nature of the tabulated predictions: for example, changing the amount of the film load within a cooler will alter the rate at which the film cools or warms. While the tables only display temperature predictions up through a 24 hour period, the temperature rate of change by the 24 hour mark is sufficiently slow and regular that temperature predictions beyond 24 hours could be easily extrapolated through a linear procedure. It is also important to note that Tables 7-20 represent data acquired from soak tests that used a thermal blanket to shield the cooler from exposure to the ambient temperatures. As will be further compared below, the thermal blanket proved advantageous to slowing the heat gain/loss to/from the film. It is also important to note that no significant differences were seen between the core and surface temperatures (both small and large rolls) in any of the soak tests conducted with the thermal blanket except for an approximate 4 °F difference seen during the small roll cold soak test (surface colder than core by approximately 4 °F).

Furthermore, in relation to the statement made previously regarding the location of the instrumented canister within the cooler, it was noted that the film canisters in the bottom layer within the cooler were consistently colder to the touch than were those in the top layer after the completion of a "hot soak" test. This fact helped solidify the conservative nature of the collected data; the top layer warmed up more rapidly than did

the bottom layer, and, consequently, the predicted data represents heating times slightly more accelerated than may be experienced by some of the canisters in the cooler.

In a similar fashion, the thermal behavior of a VHS cassette is highly dependent upon the amount of film also present in a cooler. Relative to the small and large film canisters, the VHS cassette consists of relatively little mass. As a result, the temperature of VHS cassettes is largely and rapidly affected by the surrounding air and contacting surface temperatures. The temperature of the ambient air within a closed cooler is in turn a direct function of the temperature of the film mass within the cooler. Consequently, the cooling and heating behavior of a VHS cassette is directly proportional to the amount of and temperature of additional film within the cooler. While the film canisters also show this dependence, the small mass of the VHS lends itself to much more rapid temperature changes and thermal response times, and the VHS cassette reached "steady-state" conditions much sooner than the film rolls.

In situations where the unpowered cooler was immersed in warm environments such that the film heated up with time, the VHS cassette and the small film roll average temperatures generally lagged behind the cooler's internal air temperature by 5-15 °F. The largest difference between the cooler internal temperature and the VHS/small film roll temperatures occured during the first 5 hours of the soak test, with the difference gradually decreasing over the balance of the 24 hour time period. However, it is evident from some of the experimental data that the position in which the VHS cassette is placed relative to the film canisters also affects the VHS temperature. For example, if the portion of the VHS cassette containing the thermocouple were in close proximity to or were touching film canisters, the conductive and radiative heat exchange between the cassette and canister could maintain the cassette at temperatures closer to the canister temperature than to the cooler's internal air temperature.

In situations where the unpowered cooler was immersed in environments colder than the initial cooler and film temperature, the VHS and small film roll temperatures lagged behind the cooler's internal air temperature slightly more than in the heating situations. The film temperatures, in the first 10 hours of the experiments, were as much as 20 °F warmer than the cooler air temperature. Without the thermal blanket on the cooler, the difference in temperature between 10 and 20 hours decreased to the point where the VHS and the cooler air temperatures were almost equivalent. With the blanket, however, the VHS temperature was still approximately 8 °F warmer than the cooler's internal temperature at the end of the 24 hour period. Again, the positioning of a VHS cassette relative to other film in the cooler can affect the cassette's temperature such that the cassette may or may not follow the patterns mentioned above.

The thermal response of the large film roll was much slower than both the VHS and small roll. However, it must be emphasized that the relative amounts of film involved with the two coolers were quite disparate; the total weight of the large canisters in Cooler 3 was approximately 92 pounds, and the combined weight of the small canisters and VHS cassette in Cooler 1 was roughly 30 pounds. The large film roll average temperature lagged behind the cooler internal temperature by approximately 10 °F during the hot soak tests, and by approximately 35 °F during the cold soak test.

The important conclusion to draw in regards to the thermal behavior of VHS cassettes is their temperature can be easily affected by the amount of and temperature of film present within the same cooler, as well as being affected by the relative positioning of the film and VHS cassettes within the cooler. Consequently, without substantial film mass loaded into the cooler, a VHS cassette may be cooled or heated beyond required storage temperature limits during extended cold/hot soaks.

Relative to the soak tests conducted without the cooler's thermal blanket, the test data from soak tests using the blanket reveal some gains in terms of "end-of-test" temperatures and heating/cooling rates. The film temperatures at the end of the 24 hour

tests using the blanket were generally about 8 °F warmer for the cold soak tests and about 8 °F cooler for the hot soak tests. While this gain may not seem significant, the heating/cooling rates achieved through the use of the thermal blanket are quite notable. For example, the large film core in one hot soak test (film initially at 0 °F, ambient at 131 °F) increased in temperature between 20 and 60 °F in 13 hours without a thermal blanket, but completed the same temperature rise in 16 hours with a blanket installed. Likewise, the small film core required 9 hours to warm between 20 and 80 °F without a blanket and 11 hours with a blanket. These examples are representative of the thermal and time advantages gained through the use of a thermal blanket to cover the film coolers. In addition, it must be restated that the quiescent air ambient typical within an closed aircraft will also prove to slightly increase the time required for film to heat and cool, thus making an apparent improvement to a cooler's capability to protect film from ambient temperature conditions.

3.2 Heater Tests

After review of the test results from all three heater test sequences, ASC/AMA determined that the heater was not warming the film in a time period short enough to satisfy mission requirements. Consequently, specifics as to these original test results are not presented here. However, some general statements can be made based upon the data generated from the initial series of heater tests. For example, it was decided that the 70 ° F thermostat setting was much too low to satisfy the customer's requirements. In addition, it was found that the large ambient temperature range tested (-67 °F to 0 °F) did not greatly affect the heating rate seen in the data. In other words, even the 67 °F temperature difference between the high and low ambient temperatures only slightly affected the rate at which the film was heated. Likewise, the full- and half-full

Table 7. "Cold Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **-14 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

110	109	107	106	105	103	102	101	99	98	97	95	94	93	91	90	89	87	86	85	83	82	81	79	78
105	104	102	101	100	98	97	96	94	93	92	90	89	88	86	85	84	82	81	80	78	77	76	74	73
100	99	97	96	95	93	92	91	89	88	87	85	84	83	81	80	79	77	76	75	73	72	71	69	68
95	94	92	91	90	88	87	86	84	83	82	80	79	78	76	75	74	72	71	70	68	67	66	64	63
90	89	87	86	85	83	82	81	79	78	77	75	74	73	71	70	69	67	66	65	63	62	61	59	58
85	84	82	81	80	78	77	76	74	73	72	70	69	68	66	65	64	62	61	60	58	57	56	54	53
80	79	77	76	75	73	72	71	69	68	67	65	64	63	61	60	59	57	56	55	53	52	51	49	48
75	74	72	71	70	68	67	66	64	63	62	60	59	58	56	55	54	52	51	50	48	47	46	44	43
70	69	67	66	65	63	62	61	59	58	57	55	54	53	51	50	49	47	46	45	43	42	41	39	38
65	64	62	61	60	58	57	56	54	53	52	50	49	48	46	45	44	42	41	40	38	37	36	34	33
60	59	57	56	55	53	52	51	49	48	47	45	44	43	41	40	39	37	36	35	33	32	31	29	28
55	54	52	51	50	48	47	46	44	43	42	40	39	38	36	35	34	32	31	30	28	27	26	24	23
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature decreases.

Table 8. "Cold Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **-30 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**

Initial (°F)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
110	108	105	103	101	98	96	94	92	89	87	85	82	80	78	75	73	71	68	66	64	61	59	57	55
105	103	100	98	96	93	91	89	87	84	82	80	77	75	73	70	68	66	63	61	59	56	54	52	50
100	98	95	93	91	88	86	84	82	79	77	75	72	70	68	65	63	61	58	56	54	51	49	47	45
95	93	90	88	86	83	81	79	77	74	72	70	67	65	63	60	58	56	53	51	49	46	44	42	40
90	88	85	83	81	78	76	74	72	69	67	65	62	60	58	55	53	51	48	46	44	41	39	37	35
85	83	80	78	76	73	71	69	67	64	62	60	57	55	53	50	48	46	43	41	39	36	34	32	30
80	78	75	73	71	68	66	64	62	59	57	55	52	50	48	45	43	41	38	36	34	31	29	27	25
75	73	70	68	66	63	61	59	57	54	52	50	47	45	43	40	38	36	33	31	29	26	24	22	20
70	68	65	63	61	58	56	54	52	49	47	45	42	40	38	35	33	31	28	26	24	21	19	17	15
65	63	60	58	56	53	51	49	47	44	42	40	37	35	33	30	28	26	23	21	19	16	14	12	10
60	58	55	53	51	48	46	44	42	39	37	35	32	30	28	25	23	21	18	16	14	11	9	7	5
55	53	50	48	46	43	41	39	37	34	32	30	27	25	23	20	18	16	13	11	9	6	4	2	0

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature decreases.

Table 9. "Cold Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **-45 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**

110	107	104	101	98	95	92	89	87	84	81	78	75	72	69	66	63	60	57	54	51	48	46	43	40
105	102	99	96	93	90	87	84	82	79	76	73	70	67	64	61	58	55	52	49	46	43	41	38	35
100	97	94	91	88	85	82	79	77	74	71	68	65	62	59	56	53	50	47	44	41	38	36	33	30
95	94	93	92	91	90	89	88	88	87	86	85	84	83	82	81	80	79	78	77	76	75	75	74	73
90	87	84	81	78	75	72	69	67	64	61	58	55	52	49	46	43	40	37	34	31	28	26	23	20
85	82	79	76	73	70	67	64	62	59	56	53	50	47	44	41	38	35	32	29	26	23	21	18	15
80	77	74	71	68	65	62	59	57	54	51	48	45	42	39	36	33	30	27	24	21	18	16	13	10
75	72	69	66	63	60	57	54	52	49	46	43	40	37	34	31	28	25	22	19	16	13	11	8	5
70	67	64	61	58	55	52	49	47	44	41	38	35	32	29	26	23	20	17	14	11	8	6	3	0
65	62	59	56	53	50	47	44	42	39	36	33	30	27	24	21	18	15	12	9	6	3	1	-2	-5
60	57	54	51	48	45	42	39	37	34	31	28	25	22	19	16	13	10	7	4	1	-2	-4	-7	-10
55	52	49	46	43	40	37	34	32	29	26	23	20	17	14	11	8	5	2	-1	-4	-7	-9	-12	-15
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature decreases.

Table 10. "Cold Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **-67 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature **Film Temperature (°F)**

Initial Film / Initial Cooler Internal Temperature ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
110	106	103	99	96	92	89	85	81	78	74	71	67	63	60	56	53	49	46	42	38	35	31	28	24
105	101	98	94	91	87	84	80	76	73	69	66	62	58	55	51	48	44	41	37	33	30	26	23	19
100	96	93	89	86	82	79	75	71	68	64	61	57	53	50	46	43	39	36	32	28	25	21	18	14
95	91	88	84	81	77	74	70	66	63	59	56	52	48	45	41	38	34	31	27	23	20	16	13	9
90	86	83	79	76	72	69	65	61	58	54	51	47	43	40	36	33	29	26	22	18	15	11	8	4
85	81	78	74	71	67	64	60	56	53	49	46	42	38	35	31	28	24	21	17	13	10	6	3	-1
80	76	73	69	66	62	59	55	51	48	44	41	37	33	30	26	23	19	16	12	8	5	1	-2	-6
75	71	68	64	61	57	54	50	46	43	39	36	32	28	25	21	18	14	11	7	3	0	-4	-7	-11
70	66	63	59	56	52	49	45	41	38	34	31	27	23	20	16	13	9	6	2	-2	-5	-9	-12	-16
65	61	58	54	51	47	44	40	36	33	29	26	22	18	15	11	8	4	1	-3	-7	-10	-14	-17	-21
60	56	53	49	46	42	39	35	31	28	24	21	17	13	10	6	3	-1	-4	-8	-12	-15	-19	-22	-26
55	51	48	44	41	37	34	30	26	23	19	16	12	8	5	1	-2	-6	-9	-13	-17	-20	-24	-27	-31

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature decreases.

Table 11. "Hot Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **90 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**

Initial Temp.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	56	57	57	58	59	60	61	62	63	64	64	65	66	66	67	68	68	69	69	70	70	71	71	72
50	51	52	53	54	55	56	57	58	59	60	61	62	62	63	64	65	65	66	67	67	68	68	69	69
45	46	47	48	49	51	52	53	54	55	56	57	58	59	60	61	61	62	63	64	64	65	66	66	67
40	41	42	44	45	46	47	49	50	51	52	53	54	55	56	57	58	59	60	61	61	62	63	63	64
35	36	37	39	40	42	43	45	46	47	48	50	51	52	53	54	55	56	57	58	59	59	60	61	62
30	31	33	34	36	37	39	40	42	43	45	46	47	48	50	51	52	53	54	55	56	57	57	58	59
25	26	28	30	31	33	35	36	38	39	41	42	44	45	46	47	49	50	51	52	53	54	55	55	56
20	21	23	25	27	29	30	32	34	36	37	39	40	42	43	44	45	47	48	49	50	51	52	53	54
15	17	18	20	22	24	26	28	30	32	33	35	37	38	40	41	42	44	45	46	47	48	49	50	51
10	12	14	16	18	20	22	24	26	28	30	31	33	35	36	38	39	40	42	43	44	45	46	48	49
5	7	9	11	13	16	18	20	22	24	26	28	29	31	33	34	36	37	39	40	41	43	44	45	46
0	2	4	6	9	11	13	16	18	20	22	24	26	28	29	31	33	34	36	37	38	40	41	42	43
-5	-3	-1	2	4	7	9	12	14	16	18	20	22	24	26	28	30	31	33	34	36	37	38	40	41

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature increases.

Table 12. "Hot Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **110 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film)- thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**

↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	56	57	59	60	62	63	65	66	67	68	70	71	72	73	74	75	76	77	78	79	79	80	81	82
50	51	53	54	56	57	59	60	62	63	65	66	67	68	70	71	72	73	74	75	76	77	77	78	79
45	46	48	50	51	53	55	56	58	59	61	62	64	65	66	67	69	70	71	72	73	74	75	75	76
40	41	43	45	47	49	50	52	54	56	57	59	60	62	63	64	65	67	68	69	70	71	72	73	74
35	37	38	40	42	44	46	48	50	52	53	55	57	58	60	61	62	64	65	66	67	68	69	70	71
30	32	34	36	38	40	42	44	46	48	50	51	53	55	56	58	59	60	62	63	64	65	66	68	69
25	27	29	31	33	36	38	40	42	44	46	48	49	51	53	54	56	57	59	60	61	63	64	65	66
20	22	24	26	29	31	33	36	38	40	42	44	46	48	49	51	53	54	56	57	58	60	61	62	63
15	17	19	22	24	27	29	32	34	36	38	40	42	44	46	48	50	51	53	54	56	57	58	60	61
10	12	15	17	20	22	25	27	30	32	35	37	39	41	43	45	46	48	50	51	53	54	56	57	58
5	7	10	12	15	18	21	23	26	28	31	33	35	37	39	41	43	45	47	48	50	51	53	54	56
0	2	5	8	11	14	16	19	22	25	27	29	32	34	36	38	40	42	44	45	47	49	50	52	53
-5	-3	0	3	6	9	12	15	18	21	23	26	28	30	33	35	37	39	41	42	44	46	47	49	50

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature increases.

Table 13. "Hot Soak" large film roll average temperature predictions - film roll stored within a fully loaded (eight large cannisters) and **unpowered** Norcold cooler in a **131 °F** external ambient (5 in. × 1000 ft Kodak SO-050 and Sp-884 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	57	58	60	62	64	66	68	70	72	74	75	77	78	80	81	83	84	85	86	87	89	90	91	92
50	52	54	56	58	60	62	64	66	68	70	72	73	75	77	78	79	81	82	83	85	86	87	88	89
45	47	49	51	53	56	58	60	62	64	66	68	70	72	73	75	76	78	79	80	82	83	84	85	86
40	42	44	46	49	51	54	56	58	60	62	64	66	68	70	71	73	75	76	78	79	80	81	83	84
35	37	39	42	44	47	49	52	54	56	59	61	63	65	66	68	70	72	73	75	76	77	79	80	81
30	32	35	37	40	43	45	48	50	52	55	57	59	61	63	65	67	68	70	72	73	75	76	77	79
25	27	30	33	35	38	41	44	46	49	51	53	56	58	60	62	64	65	67	69	70	72	73	75	76
20	22	25	28	31	34	37	39	42	45	47	50	52	54	56	58	60	62	64	66	67	69	71	72	73
15	17	20	23	26	29	32	35	38	41	43	46	48	51	53	55	57	59	61	63	65	66	68	69	71
10	12	15	19	22	25	28	31	34	37	40	42	45	47	50	52	54	56	58	60	62	63	65	67	68
5	8	11	14	17	21	24	27	30	33	36	39	41	44	46	49	51	53	55	57	59	61	62	64	66
0	3	6	9	13	16	20	23	26	29	32	35	38	40	43	45	48	50	52	54	56	58	60	61	63
-5	-2	1	5	8	12	15	19	22	25	28	31	34	37	40	42	44	47	49	51	53	55	57	59	61

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with eight large cannisters). Coolers loaded with less film will experience more rapid temperature increases.

Table 14. "Cold Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **-14 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

110	99	93	86	79	72	65	58	52	46	41	35	31	26	22	19	15	12	10	7	5	3	1	0	-2
105	95	89	82	75	68	62	55	49	44	38	33	29	25	21	17	14	11	9	6	4	2	1	-1	-2
100	90	84	78	71	65	59	53	47	41	36	31	27	23	19	16	13	10	8	6	4	2	0	-1	-3
95	85	80	74	68	62	55	50	44	39	34	29	25	21	18	15	12	9	7	5	3	1	-1	-2	-3
90	81	76	70	64	58	52	47	41	36	32	27	23	20	16	13	11	8	6	4	2	0	-1	-3	-4
85	76	71	66	60	55	49	44	39	34	30	25	22	18	15	12	9	7	5	3	1	0	-2	-3	-4
80	72	67	62	56	51	46	41	36	32	27	23	20	17	14	11	8	6	4	2	0	-1	-2	-4	-5
75	67	63	58	53	48	43	38	33	29	25	21	18	15	12	9	7	5	3	1	0	-2	-3	-4	-5
70	63	58	54	49	44	40	35	31	27	23	19	16	13	11	8	6	4	2	0	-1	-2	-4	-5	-6
65	58	54	50	45	41	36	32	28	24	21	17	14	12	9	7	5	3	1	0	-2	-3	-4	-5	-6
60	54	50	46	41	37	33	29	25	22	19	15	13	10	8	6	4	2	0	-1	-3	-4	-5	-6	-7
55	49	45	42	38	34	30	26	23	19	16	13	11	8	6	4	2	1	-1	-2	-3	-4	-5	-6	-7
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature decreases, while additional film will slow the cooling process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 15. "Cold Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **-30 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

Initial (°F) \ Time (hours)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
110	98	91	83	75	67	59	52	45	38	32	26	20	16	11	7	3	0	-3	-6	-8	-11	-13	-15	-16
105	93	86	79	71	64	56	49	42	35	29	24	19	14	10	6	2	-1	-4	-7	-9	-11	-13	-15	-17
100	89	82	75	67	60	53	46	39	33	27	22	17	12	8	4	1	-2	-5	-8	-10	-12	-14	-16	-17
95	84	78	71	64	57	50	43	37	31	25	20	15	11	7	3	0	-3	-6	-9	-11	-13	-15	-16	-18
90	80	73	67	60	53	46	40	34	28	23	18	13	9	5	2	-2	-4	-7	-9	-12	-13	-15	-17	-18
85	75	69	63	56	50	43	37	31	26	21	16	11	7	4	0	-3	-5	-8	-10	-12	-14	-16	-17	-19
80	70	65	59	52	46	40	34	29	23	18	14	10	6	2	-1	-4	-7	-9	-11	-13	-15	-16	-18	-19
75	66	60	55	49	43	37	31	26	21	16	12	8	4	1	-2	-5	-8	-10	-12	-14	-16	-17	-18	-20
70	61	56	51	45	39	34	28	23	18	14	10	6	3	-1	-4	-6	-9	-11	-13	-15	-16	-18	-19	-20
65	57	52	47	41	36	31	25	21	16	12	8	4	1	-2	-5	-7	-10	-12	-14	-15	-17	-18	-20	-21
60	52	48	43	37	32	27	23	18	14	10	6	2	-1	-4	-6	-9	-11	-13	-15	-16	-18	-19	-20	-21
55	48	43	39	34	29	24	20	15	11	7	4	1	-2	-5	-8	-10	-12	-14	-15	-17	-18	-20	-21	-22

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature decreases, while additional film will slow the cooling process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 16. "Cold Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **-45 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature **Film Temperature (°F)**

↓

110	96	89	80	71	62	54	45	38	30	23	17	11	5	0	-4	-8	-12	-15	-18	-21	-24	-26	-28	-30
105	92	84	76	67	59	51	43	35	28	21	15	9	4	-1	-5	-9	-13	-16	-19	-22	-24	-26	-28	-30
100	87	80	72	64	55	47	40	32	25	19	13	7	2	-3	-7	-11	-14	-17	-20	-23	-25	-27	-29	-31
95	83	76	68	60	52	44	37	30	23	17	11	5	1	-4	-8	-12	-15	-18	-21	-23	-26	-28	-30	-31
90	78	71	64	56	49	41	34	27	20	14	9	4	-1	-5	-9	-13	-16	-19	-22	-24	-26	-28	-30	-32
85	74	67	60	52	45	38	31	24	18	12	7	2	-3	-7	-11	-14	-17	-20	-23	-25	-27	-29	-31	-32
80	69	63	56	49	42	35	28	22	16	10	5	0	-4	-8	-12	-15	-18	-21	-24	-26	-28	-30	-31	-33
75	65	58	52	45	38	31	25	19	13	8	3	-2	-6	-10	-13	-17	-19	-22	-24	-27	-28	-30	-32	-33
70	60	54	48	41	35	28	22	16	11	6	1	-4	-8	-11	-15	-18	-20	-23	-25	-27	-29	-31	-32	-34
65	55	50	44	37	31	25	19	14	8	3	-1	-5	-9	-13	-16	-19	-22	-24	-26	-28	-30	-31	-33	-34
60	51	45	40	34	28	22	16	11	6	1	-3	-7	-11	-14	-17	-20	-23	-25	-27	-29	-31	-32	-33	-35
55	46	41	36	30	24	19	13	8	3	-1	-5	-9	-12	-16	-19	-21	-24	-26	-28	-30	-31	-33	-34	-35
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature decreases, while additional film will slow the cooling process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 17. "Cold Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **-67 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

110	95	86	76	66	56	46	36	27	19	11	4	-3	-9	-15	-20	-25	-29	-33	-37	-40	-43	-45	-47	-50
105	90	81	72	62	52	43	33	25	16	9	2	-5	-11	-17	-22	-26	-30	-34	-37	-41	-43	-46	-48	-50
100	85	77	68	58	49	39	30	22	14	6	0	-7	-13	-18	-23	-27	-31	-35	-38	-41	-44	-46	-49	-50
95	81	73	64	54	45	36	28	19	11	4	-2	-9	-14	-20	-24	-29	-32	-36	-39	-42	-45	-47	-49	-51
90	76	68	60	51	42	33	25	17	9	2	-4	-10	-16	-21	-26	-30	-34	-37	-40	-43	-45	-48	-50	-51
85	72	64	56	47	38	30	22	14	7	0	-6	-12	-18	-22	-27	-31	-35	-38	-41	-44	-46	-48	-50	-52
80	67	60	52	43	35	27	19	11	4	-2	-8	-14	-19	-24	-28	-32	-36	-39	-42	-44	-47	-49	-51	-52
75	63	55	48	39	31	23	16	9	2	-5	-10	-16	-21	-25	-30	-33	-37	-40	-43	-45	-47	-49	-51	-53
70	58	51	44	36	28	20	13	6	-1	-7	-12	-18	-22	-27	-31	-35	-38	-41	-43	-46	-48	-50	-52	-53
65	53	47	39	32	24	17	10	3	-3	-9	-14	-19	-24	-28	-32	-36	-39	-42	-44	-47	-49	-51	-52	-54
60	49	42	35	28	21	14	7	1	-5	-11	-16	-21	-26	-30	-34	-37	-40	-43	-45	-47	-49	-51	-53	-54
55	44	38	31	24	18	11	4	-2	-8	-13	-18	-23	-27	-31	-35	-38	-41	-44	-46	-48	-50	-52	-54	-55
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature decreases, while additional film will slow the cooling process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 18. "Hot Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **90 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**

Initial Temp.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	56	58	60	62	64	66	67	69	70	71	73	74	74	75	76	77	77	78	79	79	80	80	81	81
50	52	54	56	58	60	62	64	66	67	69	70	71	72	73	74	75	76	76	77	78	78	79	79	80
45	47	49	52	54	57	59	61	63	64	66	68	69	70	71	72	73	74	75	75	76	77	77	78	78
40	42	45	47	50	53	55	58	60	62	63	65	66	68	69	70	71	72	73	74	75	75	76	76	77
35	37	40	43	46	49	52	54	57	59	61	63	64	66	67	68	69	70	71	72	73	74	74	75	76
30	32	36	39	42	45	48	51	54	56	58	60	62	63	65	66	67	69	70	71	71	72	73	74	74
25	28	31	35	38	42	45	48	51	53	55	58	59	61	63	64	65	67	68	69	70	71	72	72	73
20	23	26	30	34	38	42	45	48	50	53	55	57	59	61	62	64	65	66	67	68	69	70	71	72
15	18	22	26	30	34	38	41	45	47	50	53	55	57	59	60	62	63	64	66	67	68	69	70	70
10	13	17	22	26	31	35	38	42	45	47	50	52	54	56	58	60	61	63	64	65	66	67	68	69
5	8	13	18	22	27	31	35	39	42	45	48	50	52	54	56	58	60	61	62	64	65	66	67	68
0	3	8	13	18	23	28	32	36	39	42	45	48	50	52	54	56	58	59	61	62	63	65	66	67
-5	-1	4	9	14	20	24	29	33	36	39	43	45	48	50	52	54	56	58	59	61	62	63	64	65

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature increases, while additional film will slow the heating process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 19. "Hot Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **110 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ **Film Temperature (°F)**

Initial Film / Initial Cooler Internal Temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	57	60	63	66	69	72	74	77	79	81	83	84	86	87	88	89	90	91	92	93	94	94	95	96
50	52	56	59	62	65	68	71	74	76	78	80	82	83	85	86	87	89	90	91	91	92	93	94	94
45	48	51	55	58	62	65	68	71	73	75	78	79	81	83	84	85	87	88	89	90	91	92	92	93
40	43	46	50	54	58	62	65	68	70	73	75	77	79	81	82	84	85	86	87	88	89	90	91	92
35	38	42	46	50	54	58	61	65	67	70	73	75	77	79	80	82	83	84	86	87	88	89	90	90
30	33	37	42	46	51	55	58	62	65	67	70	72	74	76	78	80	81	83	84	85	86	87	88	89
25	28	33	38	42	47	51	55	59	62	65	68	70	72	74	76	78	80	81	82	84	85	86	87	88
20	23	28	33	38	43	48	52	56	59	62	65	68	70	72	74	76	78	79	81	82	83	85	86	87
15	19	24	29	34	40	44	49	53	56	59	63	65	68	70	72	74	76	78	79	81	82	83	84	85
10	14	19	25	30	36	41	45	49	53	57	60	63	66	68	70	72	74	76	78	79	80	82	83	84
5	9	15	21	27	32	37	42	46	50	54	58	61	63	66	68	70	72	74	76	77	79	80	82	83
0	4	10	16	23	28	34	39	43	48	51	55	58	61	64	66	69	71	73	74	76	77	79	80	81
-5	-1	6	12	19	25	30	36	40	45	49	53	56	59	62	64	67	69	71	73	74	76	77	79	80

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature increases, while additional film will slow the heating process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

Table 20. "Hot Soak" small film roll average temperature predictions - film roll stored within a partially loaded (five small cannisters and one VHS tape) and **unpowered** Norcold cooler in a **131 °F** external ambient (5 in. × 350 ft Kodak 2430 and 2494 Sp-883 film) - thermal jacket on cooler.

Initial Film / Initial Cooler Internal Temperature ↓ — **Film Temperature (°F)**; columns: **Time (hours)**

↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
55	58	62	66	71	75	78	82	85	88	91	93	95	97	99	101	102	104	105	106	107	109	109	110	111
50	53	57	62	67	71	75	79	82	85	88	91	93	95	97	99	100	102	103	105	106	107	108	109	110
45	48	53	58	63	67	71	75	79	82	85	88	91	93	95	97	99	100	102	103	104	106	107	108	109
40	44	48	54	59	63	68	72	76	79	83	86	88	91	93	95	97	98	100	101	103	104	105	106	107
35	39	44	49	55	60	65	69	73	77	80	83	86	88	91	93	95	97	98	100	101	103	104	105	106
30	34	39	45	51	56	61	66	70	74	77	81	83	86	89	91	93	95	97	98	100	101	102	104	105
25	29	35	41	47	52	58	62	67	71	75	78	81	84	86	89	91	93	95	97	98	100	101	102	103
20	24	30	37	43	49	54	59	64	68	72	76	79	82	84	87	89	91	93	95	97	98	100	101	102
15	19	26	32	39	45	51	56	61	65	69	73	76	79	82	85	87	89	91	93	95	97	98	100	101
10	15	21	28	35	41	47	53	58	62	67	71	74	77	80	83	85	88	90	92	94	95	97	98	100
5	10	17	24	31	38	44	49	55	60	64	68	72	75	78	81	83	86	88	90	92	94	95	97	98
0	5	12	20	27	34	40	46	52	57	61	66	69	73	76	79	82	84	86	88	90	92	94	95	97
-5	0	8	15	23	30	37	43	49	54	59	63	67	71	74	77	80	82	85	87	89	91	92	94	96

Time (hours)

NOTE: These predicted time/temperature relationships are valid only in the situation tested (a cooler loaded with five small cannisters and one VHS tape). Coolers loaded with less film will experience more rapid temperature increases, while additional film will slow the heating process. Qualitative statements regarding the thermal behavior of the VHS cassette are recorded in the text of the report.

loads, as indicated by the large film roll average temperature, heated at near-identical rates.

In order to meet the stipulations of the mission requirements, various modifications were made to the heater and test procedure in order to improve the rate at which the film was heated. The physical changes to the heater were made in order to decrease heat losses to the ambient and the flow of cold ambient air into the heater. Additional insulation was placed into the void located between the bottom of the lower film trays and the bottom of the heater. Weather stripping was added to the sealing edges of the heater lid, and draw-down latches were installed to tightly close the lid. In addition, an insulating jacket was sewn to fit over the top two-thirds of the heater. The jacket was fastened to the front and back of the heater with strips of Velcro material. Moreover, the set point of the thermostats controlling the heater pads was increased to 130 °F.

Heater modifications made primarily for purposes of safety and ease-of-use included the installation of a braided steel cord to hold the heater lid in an open position without damaging the hinge. Furthermore, the height of the film tray dividers was decreased to facilitate the removal of the large film canisters. Previous to this modification, the large canisters were exceptionally difficult to grasp as a result of the small space provided between the canister and dividers.

Convection around the heater was minimized by placing the heater on a thin rubber pad to eliminate the air flow the bottom of the heater was subject to previously. The rubber pad also provided the electrical insulation needed to preclude additional noise in the thermocouple readings. Wooden boards were placed lengthwise against the front and back surfaces of the heater to provide some additional protection against the direct cooling effect of the convective environment in the chamber. However, the boards provided minimal shielding from the convective air currents, and the results may consequently be considered conservative relative to a situation involving quiescent

ambient air. Placing the heater onto the flat surface was representative of the actual position the heater will assume while on board the aircraft.

So as to more carefully observe the highest possible film surface temperature, the instrumented canisters were carefully positioned during the enhanced heater tests; the instrumented canisters were placed in more central film slots (which had been shown to be the warmest locations along the length of the film tray), and the surface thermocouple was positioned directly at the bottom of the film tray. The film loading pattern for tests with the enhanced heater - using a half-full film load - is shown in Figure 13. Likewise, the modified heater film loading patterns for the half-full, partially-inoperative and for the full film load heater tests are shown in Figures 14-15, respectively.

The experimental test conditions for the enhanced heater are outlined in Table 21.

Table 21. Test Conditions for Modified Heater Tests

Film Load*	Initial Film Temperature	Chamber Setting
Half	-10	-67
Half	-10	-30
Half	-10	0
Half	-10	30
Half	-10	60
Half	30	-67
Half	30	-30
Half	30	0
Half	30	30
Half	30	60
Full	-10	-30
Full	30	-67
Half/PI	-10	-30
Half/PI	30	-30

*Half = four large and one small film canisters, two VHS cassettes
Full = eight large and two small film canisters, three VHS cassettes
Half/PI = half load, partially inoperative (back bottom tray unpowered)
(all temperatures in table expressed in °F)

The tests to examine the performance of the enhanced heater were conducted with the thermostats set at 130 °F. The test parameters, as presented in Table 21, include ambient temperatures not used in the test sequences performed prior to the heater modifications. These additional ambient temperatures, however, had been written into the scope of the original Project Plan documentation.

The new test results indicated, as had been seen in tests previous to the heater modifications, that the ambient temperature, even over the -67 to 60 °F range, had a relatively small effect upon the heating rate of the film. Likewise, the full film load and the partially inoperative tests proved to also have small effects upon the film's heating rate (only slightly decreased relative to the half-full cases). Consequently, the average temperature predictions for the small and large film rolls under the three different test configurations (half-full, full, and partially inoperative) can be expressed as in Tables 22-23, respectively. However, it is estimated that if both the top and bottom heater blankets on one side of the heater were to fail, the effect upon the heating process for film placed in the functional tray would be an approximate 10 °F decrease in the film temperature at the end of a 2 hour heating period. As noted on the tables, the surface temperature of the large film rolls, after 2 hours of heating, was 35 to 45 °F warmer than the large film roll core temperature. Similarly, the small roll surface temperature was 15 to 20 °F warmer than the small roll core temperature after 2 hours of heating. In the full- and half-full, partially inoperative test configurations, these temperature differences (at the end of 2 hours of heating) increased to 40-50 °F for the large roll and 20-25 °F for the small roll.

It was found that, depending upon the circumstances of the particular test configuration, one-half to one and one-quarter hours of heating time would warm the VHS cassette to a temperature range between 40 and 100 °F, respectively. The VHS cassette temperature, however, appeared to be more dependent upon the test configuration. The VHS temperature consistently reached approximately 80 °F after

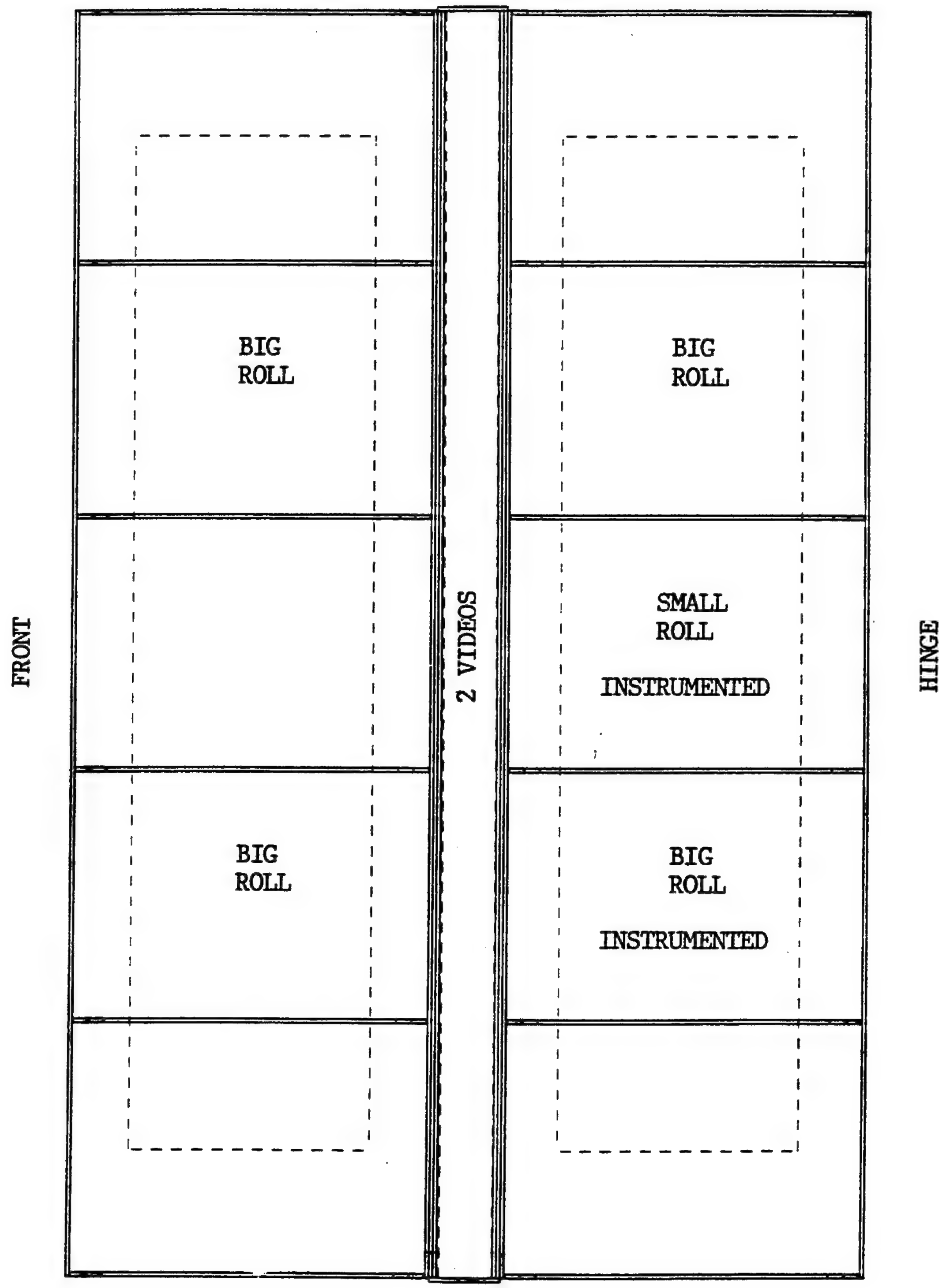

Figure 13. Film loading pattern for half-full heater tests (modified heater).

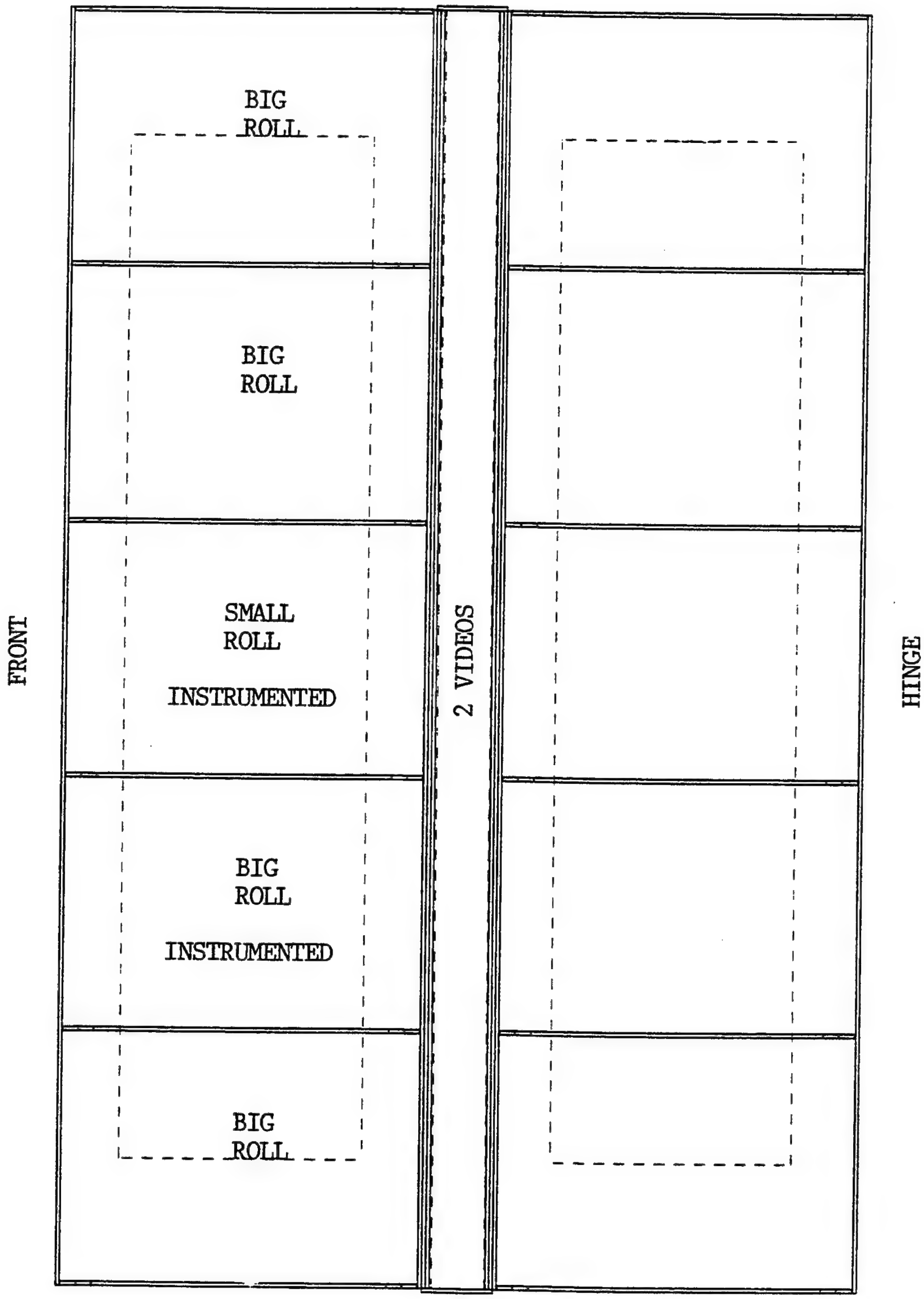

Figure 14. Film loading pattern for half-full, partially-inoperative heater tests (modified heater)

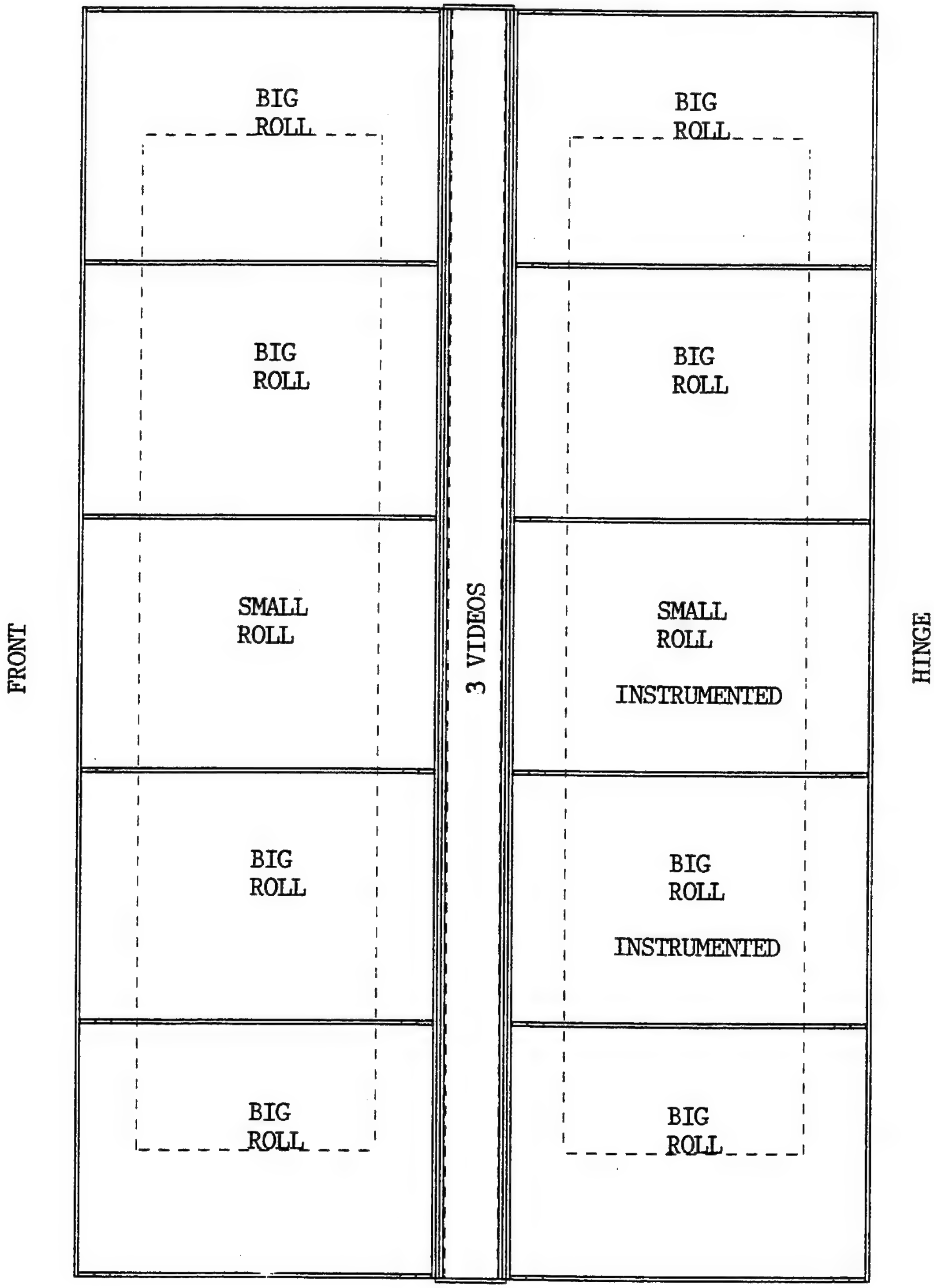

Figure 15. Film loading pattern for full heater tests (modified heater).

one hour of heating in the standard half film load tests, but this temperature required up to one-half of an hour more to reach 80 °F in the full-load and partially inoperative tests. In order to maintain the VHS media temperature below the maximum storage/operating temperature (104 °F), it must not be allowed to remain in the heater for longer than one and one-quarter hours in the standard half-full configuration and one and one-half hours in the full- and half-full, partially inoperative configurations.

During a typical mission, Tables 22-23 could be used to determine the time at which the film could be removed from the heater in order to arrive at a desired temperature. For example, if the ambient temperature on the aircraft were approximately 70 °F (and, thus, the desired film temperature is also 70 °F), the operator would note the film's initial temperature in the tables and locate the time at which the small and large rolls' average temperatures reach 70 °F. At the end of these time periods (the small roll reaching 70 °F before the large roll), the operator could remove the film from the heater and allow it to sit in the 70 °F ambient to arrive at a more equilibrium condition. As was found in one trial experiment similar to the procedure described above, the small and large rolls' surface and core temperatures appear to be able to come to an equilibrium condition within approximately one hour. Consequently, it is felt that removing the film from the heater at the time the predicted average film temperatures equal the aircraft ambient temperature (or other ambient where the film will be stored) and allowing the film to stabilize for approximately one hour in the ambient will produce a fairly equal temperature distribution, near the ambient temperature, within the film body.

However, when the film surface temperature must be kept below a particular threshold temperature to avoid damaging the film, a more careful look at the bulk temperature must be made. If, for example, this maximum threshold were 95 °F, an examination of the experimental data revealed that the bulk temperature of the large film roll was almost consistently approximately equal to 70 °F at the point when the surface reached 95 °F. This point in time generally occurred between one-and-one-half and 2

hours after the beginning of the experimental heating procedure. However, for film with a higher initial temperature (the highest tested in the experiments was 30 °F), the bulk temperature will reach this point sooner. In a similar manner, the bulk temperature of the small roll was found to be near 85 °F for a supposed surface temperature threshold of 95 °F.

3.3 Film Stabilization Tests

After the initial film stabilization tests, as specified in the project plan, were completed, it was felt that additional tests were necessary in order to more accurately predict information for higher film temperatures. Consequently, film initialized to 55 °F was heated in ambients of both 90 °F and 131 °F to provide the necessary data for film heating at higher initial film temperatures. The average temperatures of the large and small film rolls and the temperature of the VHS cassette were used to predict the time/temperature warming behavior of film at conditions other than those tested. The transition equation, Equation (1), was successfully used for this purpose. The tabulated film heating predictions are displayed in Tables 24-26 for the large roll, small roll, and VHS cassette, respectively.

As a matter of interest, an additional test was conducted to demonstrate the cooling rate of the large and small film rolls and VHS cassette. As done for the film heating tests, the film was covered to minimize enhanced cooling due to convection. The test conditions required the film be initialized to 70 °F, after which the chamber was quickly cooled to -10 °F.

It needs to be emphasized again the great importance of the effect of thermal mass in heating and cooling situations. The data in the film stabilization tables represent situations where the three film types were exposed to temperature extremes while essentially unprotected by any additional thermal mass. Grouping film canisters

Table 22. Small film roll average temperature predictions - film roll heated within a half-full (four large film canisters, one small canister and two VHS cassettes) film heater - thermal jacket on heater.

Initial Film Temperature ↓ / **Film Temperature (°F)** / **Time (hours)**

Initial Film Temperature ↓	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
60	63	68	73	77	81	85	89	92	95	98	101	103	105	107	108
55	59	63	68	73	78	82	86	90	93	96	99	101	103	105	107
50	54	59	64	70	75	79	83	87	91	94	97	99	101	104	105
45	49	55	60	66	71	76	81	85	88	92	95	97	100	102	104
40	44	50	56	62	68	73	78	82	86	89	93	95	98	100	103
35	39	46	52	58	64	70	75	79	83	87	91	94	96	99	101
30	35	41	48	55	61	67	72	77	81	85	89	92	95	97	100
25	30	37	44	51	58	64	69	74	79	83	87	90	93	96	98
20	25	32	40	47	54	61	66	72	76	81	85	88	91	94	97
15	20	28	36	44	51	57	63	69	74	78	83	86	90	93	95
10	16	24	32	40	47	54	61	66	72	76	81	84	88	91	94
5	11	19	28	36	44	51	58	64	69	74	78	83	86	89	93
0	6	15	24	32	41	48	55	61	67	72	76	81	84	88	91
-5	1	10	20	29	37	45	52	59	64	70	74	79	83	86	90
-10	-3	6	15	25	34	42	49	56	62	68	72	77	81	85	88
-15	-8	1	11	21	30	39	46	53	60	65	70	75	79	83	87
-20	-13	-3	7	17	27	36	43	51	57	63	68	73	78	82	85

NOTE: These predicted time/temperature relationships are valid for full loads of film and for situations where one heater film tray is unheated (half-load of film would be in the functioning film tray in this case). The film surface temperature was approximately 15 to 20 °F warmer than the core temperature after two hours of heating in the half-full configuration, and 20 to 25 °F warmer in the full- and half-full, partially inoperative configurations.

Table 23. Large film roll average temperature predictions - film roll heated within a half-full (four large film canisters, one small canister and two VHS cassettes) film heater - thermal jacket on heater.

Initial Film Temperature ↓	Film Temperature (°F)														
60	64	68	71	75	77	80	82	85	87	89	91	92	94	96	97
55	60	64	68	71	74	77	79	82	84	86	88	90	92	94	95
50	55	60	64	67	70	74	76	79	82	84	86	88	90	92	94
45	51	55	60	63	67	70	73	76	79	82	84	86	88	90	92
40	46	51	56	60	64	67	70	74	76	79	82	84	86	88	90
35	41	47	52	56	60	64	67	71	74	77	79	82	84	87	89
30	37	42	48	52	57	61	64	68	71	74	77	80	82	85	87
25	32	38	44	49	53	58	61	65	69	72	75	78	80	83	85
20	28	34	40	45	50	54	58	62	66	69	73	76	79	81	84
15	23	30	36	41	46	51	56	60	63	67	70	74	77	79	82
10	18	25	32	38	43	48	53	57	61	65	68	71	75	78	80
5	14	21	28	34	40	45	50	54	58	62	66	69	73	76	79
0	9	17	24	30	36	41	47	51	56	60	64	67	71	74	77
-5	4	13	20	27	33	38	44	48	53	57	61	65	69	72	75
-10	0	8	16	23	29	35	41	46	50	55	59	63	67	70	74
-15	-5	4	12	19	26	32	38	43	48	53	57	61	65	69	72
-20	-9	0	8	15	22	29	35	40	45	50	55	59	63	67	70
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0

Time (hours)

NOTE: These predicted time/temperature relationships are valid for full loads of film and for situations where one heater film tray is unheated (half-load of film would be in the functioning film tray in this case). The film surface temperature was approximately 35 to 45 °F warmer than the core temperature after two hours of heating in the half-full configuration, and 40 to 50 °F warmer in the full- and half-full, partially inoperative configurations.

together in close, compact form will help to preserve the film's temperature for longer time periods than those reflected in the tables. This can be made clear by reference to the cooling test mentioned in the previous paragraph. In this particular test, the large film core cooled from nearly 70 °F to 0 °F in approximately 7 hours. In comparison, the large film core, when placed, along with seven other large canisters into a cooler operating at a 0 °F set point (already having been stabilized at 0 °F), was able to cool from almost 80 °F to only 35 °F in approximately eight and one-half hours.

This relatively slower cooling time is primarily due to the additional thermal mass inside the cooler, as well as the effect the warm film had upon the cooler's ability to maintain an internal 0 °F ambient. In fact, the act of opening the cooler in a warm ambient, thus allowing some warm air to mix with the cool air inside the cooler, and placing warm film inside the cooler can drastically change the internal temperature of the cooler. For example, when the load of eight large canisters at 80 °F was placed into the cooler operating at 0 °F, the temperature of the air inside the cooler rapidly jumped to approximately 25 °F and only reached 0 °F again after almost 8 hours of continuous operation at the cooler's maximum setting (cooler was immersed in an 80 °F ambient during the experiment). While this particular example was an extreme situation, each test requiring the loading of film into a cooler operating at a relatively colder temperature displayed this characteristic warming of the cooler's internal cavity. However, the bulk mass of the film inside the cooler most probably affected the cooler's internal temperature much more than the warm air that was allowed to mix with the cool air inside the cooler. Therefore, the act of opening the cooler periodically should not greatly affect the results predicted in the tables. Care should be taken, however, to ensure the coolers be opened as infrequently as possible and for minimal lengths of time. While the cooler internal temperature was often affected greatly by opening it and by inserting warm film, the heater did not appear to be as affected by opening it for short periods of time (long periods would begin to affect the film heating as the film would

subsequently be heated on only one side while the other side would be exposed to the ambient).

3.4 Additional Testing and Miscellaneous Information

The catalog information describing the operating performance limitations of the Omega temperature controllers differed with the literature accompanying the product in regards to the controllers' minimum operating temperature. Consequently, it was desired to investigate this minimum temperature and the behavior of the controllers near the minimum limit specified. All four controllers used in the heater tests were placed inside the large environmental chamber with plastic sheet wrapped and taped loosely around the group of controllers to minimize the "wind-chill" effect resulting from the convective air cooling. The controllers were stabilized at 25 °F, after which the temperature was dropped to 15 °F. The temperature was decreased by 1 °F every 5 minutes until at a chamber setting of 9 °F and a displayed temperature of approximately 9.5 °F, some of the controllers began to blink an error message which indicated a condition outside the controllers' operating range. The literature sent with the controllers had stated the minimum operating temperature to be 14 °F, and the experiment showed that this temperature would be a safe limit to suggest for best performance of the controllers.

The original project plan called out for two temperature controllers to regulate the upper and lower halves, respectively, of the film heater. When wired as such, the circuitry required the use of relay switches to adequately handle the current draw requirements of the heater pads relative to the maximum current allowed by the controllers' switch contacts. However, it was decided that four controllers - one per heater pad - would create a safer situation. With only one controller regulating the bottom portion of the heater, for example, the temperature signal sent to the controller references one specific location on the heater surface. If this thermocouple were to become disattached from the heater surface, the signal sent to the controller would

represent a colder temperature than that actually sensed at the heater surface. As a consequence, a "thermal runaway" condition could result which could damage the film or even cause a fire.

By controlling each heater pad separately, this problem can be reduced to a potential runaway of one heater pad rather than two together. The hardware could further be enhanced for safe operation by placing a thermal switch, mounted to each heater pad, in line with each controller. The thermal switch could be manufactured to open at a present maximum temperature, thus limiting the extent to which a heater pad could enter a runaway condition if the thermocouple were to be loosed from full contact with the heater surface.

As a consequence of the intimate contact between the bottom heater trays and the film, and lack of such contact between the film and the upper heater trays, the upper heater trays reach their maximum setpoint temperature more rapidly upon startup than do the bottom heater trays. In addition, the controllers governing power to the heater pads on the bottom cycled more frequently than those governing the top as a result of the more rapid energy flow from the bottom heaters to the film (a consequence of the contact between the bottom and the film).

It was also noted that slight damage occurred to some corners of the plastic portion of the cooler lids. As a consequence of the thermal and mechanical stresses placed upon the lids during testing (high- and low-temperature cycling coupled with the forces induced by the tight fit against the sealing surfaces), some small cracks appeared in the plastic that reached from the outside edge into the depression molded into the lid to accommodate the rubber seal.

4.0 CONCLUSIONS

Time/temperature relationships were developed and predicted from experimental procedures to facilitate the usage of film coolers and a film heater in the process of preparing photographic and video media to desired average temperatures. It is recommended that, when possible, film be stored in as large a quantity as possible to provide thermal mass sufficient to protect the film from extreme temperatures during extended hot or cold "soak" exposure.

Large Film Roll: Film Warming to 60 °F - Average Film Temperature																			
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																		
Temperature	55	52	49	46	43	40	37	34	31	28	25	22	19	16	13	10	7	4	0
131 °F	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3
120 °F	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5
110 °F	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.6	1.7
100 °F	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8	1.9	2.0
90 °F	0.5	0.6	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.9	2.0	2.1	2.2	2.3	2.4
80 °F	0.6	0.8	1.0	1.2	1.3	1.5	1.6	1.8	1.9	2.1	2.2	2.3	2.4	2.5	2.7	2.8	2.9	3.0	3.1
70 °F	0.9	1.3	1.6	1.9	2.1	2.4	2.6	2.8	3.1	3.3	3.5	3.7	3.8	4.0	4.2	4.4	4.6	4.7	5.0

Large Film Roll: Film Warming to 70 °F - Average Film Temperature																	
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																
Temperature	65	61	57	53	49	45	41	37	33	29	25	21	17	13	9	5	0
131 °F	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.6
120 °F	0.3	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9
110 °F	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2
100 °F	0.5	0.7	0.9	1.0	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.4	2.5	2.6
90 °F	0.6	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.3	3.5
80 °F	0.9	1.4	1.8	2.1	2.5	2.8	3.1	3.3	3.6	3.8	4.1	4.3	4.6	4.8	5.0	5.2	5.5

Large Film Roll: Film Warming to 80 °F - Average Film Temperature																				
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																			
Temperature	75	71	67	63	59	55	51	47	43	39	35	31	27	23	19	15	11	7	3	0
131 °F	0.3	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.7	1.8	1.8	1.9	2.0	2.0
120 °F	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.4
110 °F	0.5	0.7	0.9	1.0	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
100 °F	0.6	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.3	3.4	3.6	3.7	3.8
90 °F	0.9	1.4	1.8	2.1	2.5	2.8	3.1	3.3	3.6	3.8	4.1	4.3	4.6	4.8	5.0	5.2	5.4	5.6	5.8	6.0

Table 24. Warming of large film roll to (a) 60 °F, (b) 70 °F and (c) 80 °F as a function of initial film and ambient (still air) temperatures

Small Film Roll: Film Warming to 60 °F - Average Film Temperature																			
Ambient Temperature	Film Warming Time in Hours for Initial Film Temperature in °F																		
	55	52	49	46	43	40	37	34	31	28	25	22	19	16	13	10	7	4	0
131 °F	0.2	0.3	0.3	0.4	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0
120 °F	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.1
110 °F	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2	1.2
100 °F	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4
90 °F	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.6	1.7
80 °F	0.5	0.6	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.2
70 °F	0.7	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.7	2.8	2.9	3.0	3.1	3.2	3.4

Small Film Roll: Film Warming to 70 °F - Average Film Temperature																	
Ambient Temperature	Film Warming Time in Hours for Initial Film Temperature in °F																
	65	61	57	53	49	45	41	37	33	29	25	21	17	13	9	5	0
131 °F	0.2	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2
120 °F	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.4
110 °F	0.4	0.6	0.7	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.0	2.1
100 °F	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9
90 °F	0.5	0.7	0.8	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
80 °F	0.7	1.0	1.3	1.5	1.7	2.0	2.1	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.4	3.5	3.7

Small Film Roll: Film Warming to 80 °F - Average Film Temperature																				
Ambient Temperature	Film Warming Time in Hours for Initial Film Temperature in °F																			
	75	71	67	63	59	55	51	47	43	39	35	31	27	23	19	15	11	7	3	0
131 °F	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5
120 °F	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.5	1.6	1.7	1.7
110 °F	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9	1.9	2.0	2.0
100 °F	0.5	0.7	0.8	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.6
90 °F	0.7	1.0	1.3	1.5	1.7	2.0	2.1	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.4	3.5	3.7	3.8	3.9	4.0

Table 25. Warming of small film roll to (a) 60 °F, (b) 70 °F and (c) 80 °F as a function of initial and ambient (still air) temperatures

VHS: Film Warming to 60 °F																			
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																		
Temperature	55	52	49	46	43	40	37	34	31	28	25	22	19	16	13	10	7	4	0
131 °F	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
120 °F	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
110 °F	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6
100 °F	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6
90 °F	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7
80 °F	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.9
70 °F	0.4	0.4	0.5	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.2

VHS: Film Warming to 70 °F																	
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																
Temperature	65	61	57	53	49	45	41	37	33	29	25	21	17	13	9	5	0
131 °F	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
120 °F	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
110 °F	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7
100 °F	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8
90 °F	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9
80 °F	0.4	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.2	1.3	1.3

VHS: Film Warming to 80 °F																				
Ambient	Film Warming Time in Hours for Initial Film Temperature in °F																			
Temperature	75	71	67	63	59	55	51	47	43	39	35	31	27	23	19	15	11	7	3	0
131 °F	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6
120 °F	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
110 °F	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8
100 °F	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.0
90 °F	0.4	0.5	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4

Table 26. Warming of VHS media to (a) 60 °F, (b) 70 °F and (c) 80 °F as a function of initial media and ambient (still air) temperatures

APPENDIX

Appendix A: Derivation of Film Temperature Averaging Procedure

The shape of the transient temperature profile within a body is dependent upon the thermal and physical properties (e.g. thermal conductivity, specific heat, density) of the material. As a first approximation to the temperature distribution within a body during the transient conditions incurred by a heating or cooling process, a parabolic expression provides a simple and fairly accurate model of the actual distribution. In addition, the particular thermophysical properties of a plastic material such as that the film is made of would tend to support a somewhat parabolic transient temperature profile.

The general expression for a parabola with vertex at (h, k) and that opens to the right $(p > 0)$ is

$$(y - k)^2 = 4p(x - h) \tag{A-1}$$

Application of this expression to the problem at hand (determining a "bulk" film temperature as a function of the surface and core temperatures) can be portrayed as shown in Figure A.1 for both heating and cooling situations.

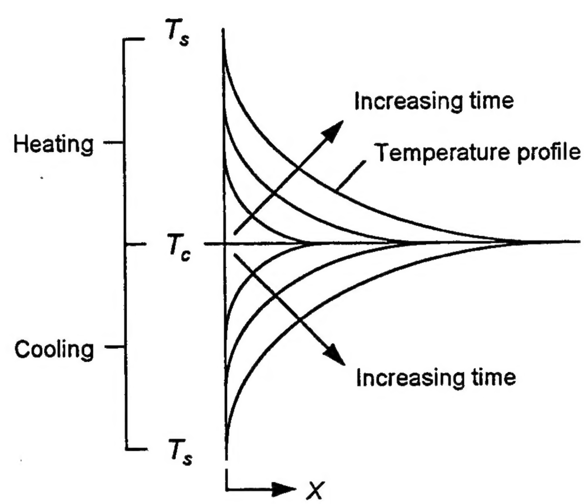

Figure A.1 Depiction of parabolic temperature distributions

T_c represents the core and initial bulk film temperature, and likewise, T_s represents the surface temperature. The normalized coordinate, X, is a measure of the distance from the surface of the film ($X = 0$) into the film body. As indicated, the parabolic temperature distribution propagates inward as time increases. It must be understood in examining Figure A.1 that T_c is not required to remain at a constant value, but that the approximate shape of the temperature profile between the surface and core is assumed to remain parabolic throughout the heating or cooling process. While the portion of the film roll between the core thermocouple site and the film spool is not taken into account in this approximation, most of the film mass is accounted for in this simple analysis and will serve as being representative of the whole film mass.

Rewriting Equation A-1 in terms of the parameters in question, the resultant expression is

$$(T - T_s)^2 = 4px \tag{A-2}$$

subject to the boundary condition that

$$T = T_c \text{ at } x = 1, \tag{A-3}$$

where the location $x = 1$ refers to the location within the film body at the site of the core thermocouple. Applying the boundary condition (A-3) to expression (A-2) yields the equality for p:

$$p = \frac{(T_c - T_s)^2}{4} \quad . \tag{A-4}$$

Making the substitution for p into Equation A-2, the resultant expression for $T(x)$ is

$$T(x) = T_s + (T_c - T_s)x^{1/2} \,, \tag{A-5}$$

which is valid for both heating and cooling situations. Now, the average value of a continuous function such as that described in Equation (A-5) is

$$\text{average value} = \frac{1}{b-a}\int_a^b f(x)\,dx \tag{A-6}$$

where a and b represent the limits of the interval over which $f(x)$ is continuous. In this particular analysis, the integral appears as

$$\int_0^1 \left[T_s + (T_c - T_s)x^{1/2}\right] dx \tag{A-7}$$

which, when evaluated, yields the expression for the bulk (average) film temperature:

$$T_{bulk} = \frac{2}{3}T_c + \frac{1}{3}T_s \,. \tag{A-8}$$

Equation (A-8) is also presented in the body of the report as Equation (2).